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INTRODUCTION

This work is the continuation of the EMR Contract OSU81-00232. It is the overall objective of this line of work to develop reliable methodology for the evaluation of surface properties of energy resources systems such as coal and heavy oils. Earlier we developed the freezing front technique for the characterization of the surface parameters of coal particles or other particulate matter. During this present contract period, we explored new independent techniques of determining the surface tension and/or contact angles of solid particles as well as liquid droplets, e.g. in emulsions. The particle surface tension was determined by means of the freezing front technique (critical velocity, V_c, measurements), and by sedimentation volume, V_{sed}. We also performed some preliminary particle adhesion measurements as a supplementary method to the freezing front technique and some direct contact angle measurements on polished coal segments as well. We have continued the study of aging of coal as related to temperature, storage, particularly oxidation effects (by oven drying or glow discharge). Some preliminary experiments on polymer adsorption on coal were also conducted.

The freezing front technique was applied to emulsions for the first time. A new method was developed for measuring the liquid/liquid interfacial tension from the shape of axisymmetric menisci. The temperature dependence of the surface tension of different industrial oils was also determined.

As auxiliary experiments, the density, specific heat of the different solid particles was measured.

Two manuscripts were accepted for publication (Chemical Engineering Communication and Colloids and Surfaces, respectively) and one paper was published during the contract period (Can. J. of Chemistry 60, 1853-1856,1982). Two more papers are in preparation.

MATERIALS AND METHODS

A. MATERIALS

1. Solid Particles

1.1 Coal Samples

Six coal samples were studied during the present contract period. They were bituminous coals: coal No.1, CNRL #1, #2 and #3, DEVCO metallurgical coal, MINTO R.O.M., originating all from Western Canada. Each of the coal samples consisted of three fractions identified by a range of -60+100, -200+325 and -400 mesh, respectively. The finest (-400 mesh) were used for the sedimentation volume measurement while the freezing front experiments were performed with the -60+100 and -200+325 mesh fractions. One portion of each sample was oven-dried at 105°C. These portions were used for specific heat measurements and also for the aging experiments. The physical properties of these coals are given in Table 1.

1.2 Clay

We studied three clay samples: (1) commercial bentonite with a particle size of approximately 0.4-1 μm in diameter; (2) kaolinite #9 (standard) from Mesa Alta, New Mexico with a particle size of 4-5 μm; and (3) MICA (No.325S dry ground) with a size of <325 mesh.

1.3 Polymer Samples

Nine different polymer powder/beads were used for the sedimentation volume experiments. Some of them were used as a polymer sheet or film for the adhesion measurements. The density, ρ, particle size, D, and solid/vapour surface tension, γ_{SV}, are summarized for polymer samples in Table 2.

2. Matrix Materials

For the freezing front experiments, three matrix materials, thymol, benzophenone and water/ice were used. The physical properties of the matrices are given in Table 3.

3. Oil Samples

The temperature dependence of the liquid/vapour interfacial tension, γ_{LV}, of six industrial oils were measured. The oil samples investigated were: Varsol, Fuel oil No.2, Leduc crude, Bachequero crude, and a coal tar: xylene (1:1 ratio) mixture. The oils were stored at room temperature in well closed bottles prior the measurements.

4. Solvents

The sedimentation volume, V_{sed}, of the various solid particles was measured in seventeen different solvent pairs. The criteria for choosing the solvent components are: (1) the solvents should be chemically inert with respect to the solid particles; (2) the density should be lower than that of the particles; (3) the boiling temperature should be reasonably high to minimize evaporation; (4) the solvent components should be miscible in all ratio with each other; and (5) the surface tension, γ_{LV}, of the mixture should cover the surface tension range required. The solvent pairs, the physical properties of the components and the surface tension range covered by the mixtures are presented in Table 4.

B. METHODS

1. Freezing Front Experiments

The critical velocity of engulfment, V_c, was determined for the coal samples with thymol and in some cases for other particles with benzophenone and water/ice as matrix materials. For details of this technique, see References 1,2,3,4.

2. Aging of Coal

Earlier experiments[5] showed that the particle surface tension, γ_{PV}, measured with freshly mined coal changes if the experiment is repeated several months or years later. Now this phenomenon was studied systematically as a function of:

1. the particle size (-60+100, -200+325 and -400 mesh fractions);

2. the atmosphere (air or N_2 gas) of storage;
3. the temperature of storage (room temperature or near 0°C in the refrigerator);
4. the type of oxidation after storage (heating in oven at 105°C or treatment by glow discharge).

The experiments were performed with DEVCO coal. The samples were ground and dry screened in our laboratory. Then the particle surface tension, γ_{pv}, of the "as received" samples was determined by the freezing front technique in September, 1982. Six months later, in February, 1983, the freezing front experiments were repeated with the different samples of DEVCO coal (see Fig. 1). Some of the samples were exposed to glow discharge for 30 minutes or 2 hours. The heat treated samples were kept in an oven at 105°C for 8 hours. The matrix material used for these freezing front experiments was thymol in all cases.

3. Sedimentation Volume, V_{sed}

The sedimentation volume, V_{sed}, was determined[6] for polymers, coal and clay samples. In the case of coal, nearly monodisperse fractions were prepared by dry screening; these fractions consist of particles with -400+500 mesh (between 28 to 38 μm in diameter). The monodisperse powder is expected to sediment with a sharp boundary and not a diffuse one as in the case of polydisperse systems. Monodisperse fractions of the polymers or clays cannot be prepared readily. Therefore, the polydisperse (commercial) powder was used for the experiments.

The V_{sed} measurements were performed as follows: 1.0 g powder was weighed into the graduated testtubes or cylinders and 10 mℓ of the liquid mixtures with different composition (but with known concentrations in vol.%) were poured into the cylinders. The surface tension, γ_{LV}, of the mixtures was determined by means of the modified Wilhelmy method before and in some cases after the sedimentation measurements at 20°C. The concentration range varied from 0 to 100%.

After adding the liquid to the solid powder, they were shaken until the powder was totally suspended in the liquid (approximately 20 minutes). The reading of the final sedimentation volume, V_{sed}, was taken at 20°C after a sufficiently long time (1 week to 10 days) so that no further change in V_{sed} occurred. The idea was to perform V_{sed} measurements in less polar (octane/decalin, cyclohexane/decalin, etc.), more polar (methanol/1.2 propandiol, n-propanol/DMSO, methanol or propanol/formamide, etc.) and aqueous mixtures (methanol or n-propanol/water, see Table 4).

4. Particle Adhesion Measurements

Experience with the freezing front technique showed up one of the limitations of the method. At very small particle size, of the order of 1 μm, Brownian motion, thermophoretic flows and the limit of the resolution of the optical microscope make the freezing front measurements impossible. Clay particles are often significantly smaller than 1 μm. Therefore, preliminary experiments were done to study the adhesion of such particles to substrates of various surface tensions as a function of the

surface tension, γ_{LV}, of the suspending liquid. The particle adhesion technique for the study of the surface tension of biological cells and bacteria was recently[7,8] developed, and we tried to apply it for industrial particulate matters.

Prior to the measurements, the microscopic slides and the polymer surfaces were cleaned carefully. The glass slides were first soaked in chromic acid for 24 hours, then rinsed with distilled water, sonicated in methanol twice for 15-20 minutes and finally dried in the oven at 105°C for several hours. The polymers were first cut into the proper size (25 x 75 mm), then sonicated three times always in fresh methanol. Finally, they were dried in air, covered with clean paper. The polymer surfaces either were available as polymer films or they were prepared by heat pressing as follows: the precleaned polymer sheet was inserted between superclean microscopic slides and these were put into the heat press between aluminum foil sheets. Then the temperature and pressure requested was set.

The polymers were pressed at their melting temperature, then the heating was turned off. The slides were kept under pressure until they had cooled down to approximately 20-30°C below the melting temperature, and then the pressure was released. The glass slides were separated from the polymer and were kept wrapped in aluminum foil in a desiccator.

Meanwhile, 0.01-0.05 g of coal powder were dispersed in 100 or 50 mℓ of liquid mixture with known concentration and surface tension. The polymer surface was tied to the bottom of a teflon

block with three wells. Then, 0.5 mℓ of coal suspension was transferred with an Eppendorf pipette into the wells and thus onto the polymeric surface. The wells were covered with a tape in order to prevent the evaporation of the liquid. The samples were kept for 3 days. The surface of the polymers were then washed for a few minutes with the same liquid mixture which was used for the preparation of each of the coal suspensions. This washing process was applied to eliminate all of the particles which did not adhere to the surface. Finally, the test surfaces with the adhering particles were air dried for one day. The number of particles (or the area covered by the adhering particles (in μm^2)) was determined using a Bausch and Lomb Omnicon TM 3000 Digital Image Analysis System (DIAS).

The polymeric surfaces which were used for coal adhesion are summarized in Table 5. The liquids used were either the aqueous solutions of DMSO (dimethylsulfoxide) with concentrations of 1 to 15 vol.% or n-propanol (50 and 10 vol.%) in water. The coal samples used were CNRL #2 and DEVCO with -400+500 mesh size.

5. Direct Contact Angle, θ, Measurements

Contact angle, θ, of liquid droplets was measured on coal segments by a sessile drop method. The process of the segment preparation was as follows:

1. Relatively large pieces of coal were cut, then one side of the segment was polished using a hand grinder with decreasing size of abrasive particles of the SiC grit papers. The finishing polish was done by a polishing wheel with a

napped polishing cloth. The direct contact angle measurements were performed with two coals (DEVCO and MINTO). The liquids used were distilled water, ethylene glycol and glycerol.

6. Freezing Front Technique Applied to Emulsions

The possibility of the determination of the interfacial tension, $\gamma_{L_1L_2}$, of oil/water (oil in water) emulsion using the freezing front technique was explored[9]. The matrix material chosen was water/ice. For this preliminary experiment, a well characterized hydrocarbon (paraffin oil) in water was studied. The density of paraffin oil, ρ, was 900 kg/m ^{3}, the thermal conductivity, k_p, was 0.020 W/mK, and the specific heat, C_p, was 2.89 mJ/kg ·K. For the stabilization of the emulsion, a small amount of protein (Bovine Albumin) prepared from fraction of V Albumin (Sigma Chemical Co., Lot #31F-9330) as stabilizing agent was added. An ENDOCAL refrigerated circulating bath provided the operating low temperature for the measuring cell (see Figs. 2a and 2b).

7. Liquid/Liquid Interfacial Tension, $\gamma_{L_1L_2}$ Determination from the Shapes of Axisymmetric Menisci

The determination of liquid/liquid interfacial tension, $\gamma_{L_1L_2}$ and contact angle from the shapes of axisymmetric menisci i.e. from sessile as well as pendant drops was developed. Besides gravity constant and density difference between the two fluid phases, only a set of coordinate points of the drop profile are necessary for the calculation.

The sessile or pendant drops were transilluminated by means of fibre optics and photographs of the drops were taken with a Nikon SMZ stereomicroscope equipped with polarizing filters. The sessile drops were placed onto a plate that could be tilted slightly thus allowing the base and contact points of the drop to be seen clearly. Substrates were chosen to produce contact angles as large as possible. Glass slides coated with a lightly fluorinated acrylic polymer (FC 721, 3M Corporation) were found quite satisfactory for this use.

Pendant drops were formed on tips of stainless steel hypodermic needles of various diameters, mounted onto a Gilmont ultra precision micrometer syringe. This syringe was attached to a Brinkman micromanipulator which permitted easy adjustment of the drop for photography.

From the enlarged photographs, several points along the drop profile were generated with a Talos 600 series digitizer. The schematic diagram of the apparatus is given in Fig. 3.

The surface tensions and contact angles from the shapes of droplets were calculated by means of a computational procedure, which minimizes the error between the directly observed curve and a theoretical Laplace curve. Details of the mathematics and the computational scheme are found elsewhere[10,11].

Water/n-butanol and SDS/cholesterol (dissolved in dibutyl/dioctylphtalate 1:1 by volume) systems were investigated.

8. Surface Tension, γ_{LV}, of Oils

The temperature dependence of the surface tension, γ_{LV}, of oils were determined by a modified Wilhelmy technique.

The oil sample in the measuring cell was kept in an inert atmosphere of argon saturated with the vapour of the oil. The measuring cell was connected to an automatic temperature control device.

A Cahn electro balance was used to measure the mass of oil which was lifted above the horizontal liquid level. This mass is proportional to the surface tension of the oil, γ_{LV}. The measurements were performed within the temperature range from 20 to 90°C, increasing and decreasing the temperature by 0.5°C/min.

9. Specific Heat, C_p, Measurements

The specific heat, C_p, of the coal samples was determined by Differential Scanning Calorimetry (DSC). The heating rate was chosen as 10 K/min, the chart range as 5 mV and the chart speed as 20 mm/min. The reference standard was a sapphire (α - $A\ell_2O_3$) disc. All measurements were carried out in an atmosphere of flowing dried N_2 gas over a temperature range of 283 to 363 K. The specific heat measurements were performed with oven-dried samples. For more details, see Reference 12.

RESULTS AND DISCUSSION

1. Freezing Front Experiments for Coal

The particle surface tension, γ_{PV}, of coal No.1, CNRL #1, 2 and 3 (-400 mesh fractions only) as well as of DEVCO metallurgical and Minto R.O.M. coal samples (-60+100, -200+325 and -400 mesh sizes) was determined by measuring the critical velocity of engulfment, V_c, using the freezing front technique.

The measurements were performed in thymol at 51.5°C with the "as received" samples in September, 1982. The results are summarized in Tables 6-9. The solidification front velocity, V, versus particle diameter, D, is plotted in Figs. 4-5 for DEVCO and MINTO coals, respectively. The corresponding plots, γ_{PV} and θ versus particle diameter, D, at 20°C are represented in Figs. 6-7 for these two coal samples.

The mean particle surface tension, γ_{PV}, of the six different coals (only for the -400 fractions) was calculated and summarized in Table 10. These fine fractions were used later for the sedimentation volume, V_{sed}, measurements and therefore the γ_{PV} data were of importance. Of the six coals, the MINTO sample has a significantly higher particle surface tension than the other samples, especially in the smaller particle size range. This finding is in agreement with the unusually high ash content and low fixed carbon content, see Table 1.

2. Study on Aging of Coal

It was concluded earlier[5] that the freezing front experiments with freshly mined, "as received" coal yielded results which could not be reproduced after a storage for longer time (months, years). This suggests that the coal powder aged during the storage. As such processes may have a strong influence on the processing of the coal, these experiments were continued to study these phenomena systematically. The change of the surface tension was monitoring by freezing front experiments which were performed with DEVCO in thymol as matrix material at 51.5°C. The surface tension, γ_{PV}, was determined for the "as received"

coal powder. The measurements were later repeated with the various aged samples.

The storage of DEVCO coal was performed under four different experimental circumstances (Fig. 1) producing four differently aged samples:

1. stored at room temperature in air;
2. stored at room temperature in N_2;
3. stored near 0°C in air;
4. stored near 0°C in N_2.

After aging, all the four samples were oven-dried at 105°C. Sample No.1 was also subjected to glow discharge.

The results are summarized in Tables 11-13 for the "as received" and aged coals (Table 11), for the aged/oven-dried samples (Table 12) and for the aged/glow discharged samples (Table 13), respectively. The particle surface tension, γ_{PV}, given at 20°C of the various samples are summarized in Table 14. The corresponding plots, γ_{PV} versus particle diameter, D, are given in Figs. 8-10.

The surface tension of the aged samples (Fig. 8) increases with increasing particle size and also depends on the temperature and the atmosphere of storage. All of the aged samples have higher particle surface tension, γ_{PV}, than the "as received" one. The coal became more hydrophilic if it was kept at room temperature than at 0°C, or if it was stored in air than in N_2. As the increasing hydrophilic character of the coal surface is attributed to a slow oxidation of coal, as expected, both the low temperature and the presence of the N_2 gas slow down this change of the surface.

The oven-drying at 105°C (Fig. 9) reduced the surface tension of all types of the aged coal slightly. The difference in γ_{PV} between the four differently stored coal powders diminished after the heat treatment. The drying process rendered the coal less hydrophilic, independent of the storage circumstances. These phenomena have already been observed earlier[5] for dry screened coal samples. One part of coal stored at room temperature in air was subsequently exposed for 30 minutes, another part for 2 hours, to glow discharge. Surprisingly, both samples treated by glow discharge became less hydrophilic than the aged or aged/oven-dried samples. However, the duration of this treatment did not affect the γ_{PV} value (Fig. 10).

For easier comparison of the effect of these various treatments on the surface tension of coal stored at room temperature in air, γ_{PV} versus particle diameter plots are summarized in Fig. 11. These plots support the conclusions that: (1) DEVCO coal had a higher γ_{PV} after six months' storage, than the "as received" sample; (2) both the temperature and the storage atmosphere influence the surface properties of coal; (3) finally, both the heat treatment and especially the glow discharge rendered the surface less hydrophilic than it was after aging.

3. Sedimentation Volume, V_{sed}, Measurements

The sedimentation volume, V_{sed}, was measured for polymers, coal powders and clays. For the V_{sed} measurements, 17 solvent pairs were used. The liquids used comprised several organic solvents with a wide range of surface tension and a few industrial oils. The solvent pairs were chosen in such a way, that

one solvent had a surface tension, γ_{LV}, lower than the surface tension of the particles, γ_{PV}, and the second solvent had a higher surface tension than the particles. The solvent mixtures in various concentrations spanned the range of surface tensions which included the surface tension of the particle, γ_{PV}.

The surface tension of the solvent mixtures are summarized in Tables 15a,b and c, while the surface tension of the various solvents (ethers and diols), as well as the γ_{LV} of the industrial oils are given in Tables 16 and 17, respectively. The surface tensions of the liquids were measured prior to the measurements at 20°C. In some cases, the surface tension of the supernatant solvent was determined after the sedimentation volume measurements as well to check if any measurable change in the γ_{LV} occurs. The surface tension of one non polar (n-hexane/cyclohexanone), one more polar (methanol/1,2,propandiol) and two aqueous solutions (methanol/water and n-propanol/water) were investigated prior and after the measurements. The results are given in Figs. 12-15. The surface tension of the solvent mixtures did not change appreciably.

The results of sedimentation volume measurements, V_{sed}, versus γ_{LV} of the liquid medium, are plotted in Figs. 16-20 and given in Tables 18-19 for polymers, in Figs. 21-45 and Tables 20-22 for the various coals and in Table 23 for clays.

It was found that the sedimentation volume changed with the composition and hence the surface tension of the liquid mixtures. In the case of the hydrophobic polymer powders such as the two teflon samples and the high density polyethylene, the

V_{sed} versus γ_{LV} of liquid goes through a minimum in less polar liquid mixtures (Figs. 16-18), while the more hydrophilic polymers (PVF, Nylon 6,6, polysulfon and acetal) show a maximum in more polar solvent mixtures (see Fig. 19 for PVF in different solvent pairs and Fig. 20 for 3 polymers in the same liquid pair). The details of V_{sed} results, as an example, are given for teflon and PE in Table 18. The data of solid/vapour surface tension, γ_{SV}, of the various polymers from contact angle or freezing front measurements are compared with the surface tension, γ_{LV}, of the extrema in the sedimentation curves. The results are summarized in Table 19. The agreement between the results obtained from sedimentation volume and freezing front or contact angle measurements is remarkable. The only difference shows up for PVF and PVenF samples whose purity was uncertain.

It is to be expected that the surface tension of the particles will be a determining factor in the interaction between particles in liquids as well as in the interaction with other phases. The question then arises what might happen for the specific case when the surface tension of the liquid, γ_{LV}, is equal to the surface tension of the particles, γ_{PV}. It was shown elsewhere that when $\gamma_{LV} = \gamma_{PV}$, it follows that the Hamaker coefficient, A_{132}, for the interaction between the particles becomes equal to zero, i.e. the van der Waals attraction between the particles becomes equal to zero. The next question then is what the implications of zero van der Waals attraction between particles might be for the sedimentation volume, V_{sed}. There

are at least two possible patterns of behaviour, depending on whether or not agglomeration of the particles at the early stages of sedimentation is possible or not.

(a) If there is no agglomeration at finite values of the van der Waals attraction, then zero van der Waals attraction implies least close packing of the sediment and hence a maximum of V_{sed}.

(b) If there is agglomeration at finite values of the van der Waals attraction at early stages of sedimentation, then this agglomeration would cease when the van der Waals attraction approaches zero. As it is well known that agglomeration leads to large sedimentation volumes because the irregularly shaped aggregates do not pack well, we would under such conditions expect minimum sedimentation volume at zero van der Waals attraction.

Clearly, we have here two possible mechanisms for the formation of the final sediment, one predicting a minimum and the other a maximum of the sedimentation volume when $\gamma_{LV} = \gamma_{PV}$.

Thus, the experimental evidence does not discriminate against either one of the two possible mechanisms described above. Instead, the results suggest that either one of these mechanisms might be operative, depending on the properties of the liquids and solids. If this pattern of behaviour can be substantiated, we would have the following behaviour in these suspensions.

In the more polar solvents, the relatively polar particles are well dispersed at all compositions of the liquid mixtures,

and the quality of packing decreases as the surface tension of the liquid mixtures approaches γ_{PV} from either side, due to decreasing van der Waals attraction. This results in a maximum V_{sed} at $\gamma_{LV} = \gamma_{PV}$.

In the more non polar liquids for the non polar particles (teflon, PE), there is a tendency for particle agglomeration. Thus, the further away γ_{LV} is from γ_{PV}, the larger the van der Waals attraction between suspended particles and the more pronounced the tendency for the particles to agglomerate, which leads to a minimum sedimentation volume at $\gamma_{LV} = \gamma_{PV}$. The polarity of both of the liquid medium and of the particles are influencing factors on the formation of the sedimentation volume. The results showed that the chemically homogeneous polymer particles follow this pattern of behaviour.

For coal particles, the results are somewhat ambiguous. Coal No.1 was the most thoroughly investigated sample (Figs. 21-32), which in the less polar solvent mixtures such as octane/decalin, cyclohexane/decalin had a minimum in V_{sed} at $\gamma_{LV} = \gamma_{PV}$ while in propanol/water or methanol/ethylenglycol, etc. (more polar solvents) the plot went through a maximum. On the other hand, this behaviour is not consistent, e.g. a minimum was found using the methanol/water solvent pair. Similar results were obtained with the other five coal samples (see Figs. 33-37 for CNRL #1, Figs. 38-39 for CNRL #2, Fig. 40 for CNRL #3, Figs. 41-43 and 44-45 for DEVCO and MINTO coals, respectively). The liquid surface tension, γ_{LV}, where the extrema were found are summarized for coal No.1 in Table 20 and for the other five

coals in Table 21. A comparison between the estimated γ_{PV} obtained from the sedimentation measurements and from the freezing front experiments for the six coal samples are given in Table 22.

In spite of the inconsistency of the results with respect to maxima and minima in V_{sed}, the agreement between the γ_{LV} for an extremum in V_{sed} and freezing front measurements of γ_{PV} are satisfactory.

Some preliminary sedimentation experiments were performed with clay minerals. The results obtained for bentonite, kaolinite and mica powders are given in Table 23. Aqueous solutions could not be used for bentonite and kaolinite because the presence of water caused swelling of the particles which led to the formation of a thixotropic system. Swelling even in more polar solvent mixtures was not noticeable, but the low γ_{PV} of the polar clay minerals indicates an oriented adsorptive layer of the organic solvent molecules making the surface of particles more hydrophobic.

In Figs. 46, 47 and 48 photographs of the sedimentation volume measurement are shown for PTFE in hexane/cyclohexanone (Fig. 46), nylon 6,6 in n-propanol/thiodiethanol (Fig. 47) and for coal No.1 in n-propanol/water (Fig. 48).

4. Particle Adhesion of Coal

A preliminary study of the adhesion of fine coal particles to substrates of various surface tensions as a function of the surface tension of the suspending liquid was performed. A simple thermodynamic model predicts that the particle adhesion

should increase with increasing surface tension of the solid substrate if the γ_{LV} of the medium in which particles are suspended is lower than the surface tension of the particles, γ_{PV}. If $\gamma_{LV} > \gamma_{PV}$, the opposite behaviour is predicted. The adhesion should become independent of the surface tension of the substrate if $\gamma_{LV} = \gamma_{PV}$. This technique, which leads to the measurement of the particle surface tension, γ_{PV}, was developed in our laboratory[7,8] and was successfully applied to the determination of the surface tension of various biological cells. Recently, a feasibility study was also performed with polymer particles.

During this contract period, several experiments were performed with coal particles. For these experiments, aqueous solutions of DMSO (dimethylsulfoxide) with different concentration were used. Some experiments were performed with n-propanol/water solutions too. In this early stage of the adhesion measurements with coal particles, we demonstrate the results with one example done with CNRL #2 coal (-400 mesh fraction) suspended in DMSO solution (3 and 15 v/v %) on substrates of low density polyethylene, LDPE, $\gamma_{SV} = 32.5$ mJ/m^2 and sulfonated polystyrene SPS, $\gamma_{SV} = 66.7$ mJ/m^2. The liquid surface tension of the 3% DMSO was 69.9 mJ/m^2 and γ_{LV} of the 15% DMSO solution was measured as 61.4 mJ/m^2 at 20°C. Figures 49-52 are the hard copies of the unprocessed image of the adhering coal particles on the polymer surfaces obtained by means of Image Analysis (Fig. 49 is for LDPE and 3% DMSO, Fig. 50 for SPS and 3% DMSO, Fig. 51 for LDPE and 15% DMSO, and finally Fig. 52

for SPS and 15% DMSO). The area (in percentage of the whole area examined) versus γ_{SV} of the substrates are plotted in Fig. 53. The above predicted pattern is indeed apparent in the plots. However, the experimental circumstances are different from those of biological particles, for which the technique was developed initially. One of the problems is that the coal and polymer particles as non-deformable substances do not allow strong adhesion because of the relatively small contact area, compared to that of biological cells. In spite of such experimental difficulties, the adhesion technique proved to be a very promising method for the determination of the particle surface tension, γ_{PV}, of various fine solid particles.

5. Direct Contact Angle Measurements on Coal

On the polished segments of coal DEVCO and MINTO, the contact angle of droplets of water, ethylenglycol and glycerol were measured by the sessile drop method. For each measurement, either a new segment or a re-polished surface was used. The results are given in Table 24. If we compare the γ_{SV} obtained from these experiments with those from the freezing front or sedimentation volume measurements for DEVCO coal, the result is satisfactory. In the case of MINTO coal, however, γ_{SV} calculated from the contact angle is markedly lower than the particle surface tension obtained from the other two measurements. This might be caused by roughness of this very heterogeneous sample with high ash and volatile matter content (see Table 1). Alternatively, the difference in γ_{SV} may be due to the difference in size: The specimen for the freezing front and V_{sed} measurements

was ground and screened coal powder. These processes might have changed the mineral composition.

6. The Application of the Freezing Front Technique for Emulsions

A feasibility study was conducted for the use of the freezing front technique as a means of characterizing interfacial tensions in a liquid/liquid system, e.g. an emulsion. The idea was to solidify an oil-in-water emulsion and to observe the interaction of the oil droplets with the approaching ice/water interface.

The solidification front velocity, V, versus droplet (particle) diameter, D, is plotted for a paraffin oil/water system in Fig. 54 and the same plot for paraffin oil/aqueous protein solution in Fig. 55. For both systems, a clear transition from engulfment to rejection was observed. The presence of the surface active protein in the water phase decreased the critical velocity by approximately an order of magnitude. Thus, the freezing front technique might be a feasible method for interfacial tension measurement of oil/water emulsions. Further development work would be required.

7. Interfacial Tension Measurement from the Shape of Axisymmetric Menisci

In order to test the method recently developed in our laboratory[10,11], the interfacial tension of water in n-butanol was determined for both sessile drops and pendant drops. Three pendant drops of different sizes are shown on the left hand side

of Fig. 56. The coordinate points taken from these profiles together with the Laplace curves fitted through these points are given on the right hand side of the same Figure. The statistical mean value of the $\gamma_{L_1L_2}$ is 1.73±0.03 mJ/m^2. Similarly, a series of five sessile drops of water in n-butanol is shown in Fig. 57 together with the interfacial tension obtained in each case. The mean of $\gamma_{L_1L_2}$ values is 1.78±0.04 mJ/m^2, in agreement with the value obtained from pendant drops and consistent with the literature value, which is 1.8 mJ/m^2.

The approach was applied to a system of very low interfacial tension too (an aqueous solution of 0.005 M sodium dodecyl sulfate (SDS) and a 1:1 mixture of dibutyl/dioctyl phtalate with small amount of cholesterol added). The mean value obtained for the whole series was 5.45±0.17x10^{-3} mJ/m^2.

The results indicated that the methods work largely independently of drop type, size and shape. For higher values of liquid/liquid interfacial tension (e.g. water/n-butanol), both pendant and sessile drops can be used equally well. However, for very low interfacial tensions (< 10^{-2} mJ/m^2), the measurement with sessile drops is easier to perform.

In practical emulsion systems, the oil/water interfacial tension is very small. The above strategy works well at very low interfacial tensions, and therefore it is hoped to pave the road for systematic studies of emulsion stability as related to oil recovery.

8. Liquid/Vapour Surface Tension, γ_{LV}, of Oils

The surface tension, γ_{LV}, of five different oil samples (Varsol, No.2 Fuel Oil, Leduc crude oil, Bachequero crude oil and coal tar/xylene in 50:50 wt/wt %) was measured by means of a modified Wilhelmy technique in the temperature range from 20 to 90°C. The surface tension was measured at least three times for each sample.

Plots of γ_{LV} versus temperature for the five oil samples are given in Figs. 58-62. The surface tension values at different temperatures are summarized in Table 25; the temperature coefficients, $\frac{d\gamma_{LV}}{dT}$ are given in Table 26.

9. Specific Heat of Coal, C_p

For the calculation of ΔF^{adh} and the γ_{PV} from the critical velocity measurements, we need the specific heats, C_p, of coal samples. The specific heat measurements were performed with dried coal samples and the results are given in Table 27. The C_p versus temperature are plotted in Fig. 63 for coal No.1, CNRL #1, #2 and #3 and in Fig. 64 for the DEVCO and MINTO samples. The difference in specific heat for these coals does not exceed the error limits.

CONCLUSIONS

The main task of this work was to develop and test new methods for the determination of the surface properties of coals and other solids both in powdered and bulk form. In addition,

new approaches were invested to study the liquid/liquid interfacial tension for purposes of stability analysis of emulsions. The following conclusions were reached:

1. The sedimentation volume, V_{sed}, measurements provided good results for polymers and coal samples in comparison with results obtained from the freezing front technique.
2. The feasibility studies on the adhesion of coal particles and the direct contact angle measurements on polished coal segments led to very promising results.
3. Aging the coal particles under different experimental circumstances (storage temperature and atmosphere, as well as the type of the oxidation after storage were varied) showed that at low temperature and in N_2 atmosphere the oxidation of coal slows down.
4. The freezing front technique was used to establish the feasibility of determination of liquid/liquid interfacial tensions, $\gamma_{L_1L_2}$, for oil/water emulsions. Experimentally, the technique works well. Theoretical development work is still needed.
5. For the determination of the interfacial tension of liquid pairs another new method was tested. The interfacial tension of two liquids can be calculated from the shapes of droplets. A computational procedure was developed for the evaluation of such measurements. The method is suitable for a wide range of interfacial tensions, including extremely low interfacial tensions ($< 10^{-2}$ mJ/m^2).

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TABLE 1. PHYSICAL PROPERTIES OF COAL SAMPLES

Physical Properties	Coal No.1 -400 mesh	CNRL #1 -400 mesh	CNRL #2 -400 mesh	CNRL #3 -400 mesh	DEVCO as received -60 mesh	MINTO as received -60 mesh
Density (kg/m^3)	1350	1340	1390	1320	1370	1357
Ash Content (wt%)	11.07	8.33	10.41	9.73	4.90	19.34
Moisture Content (wt%)	0.64	0.58	0.77	1.67	1.24	1.50
Volatiles (wt%)	20.65	19.70	20.69	20.74	34.20	34.90
Fixed Carbon (wt%)	68.28	71.97	68.90	69.53	60.90	45.76
Specific Heat at 51.5°C (kJ/kg/K)	1.15	1.10	1.11	1.08	1.16	1.12
Surface Area (m^2/kg)	4220	5130	4720	4360	320	790

TABLE 2. PHYSICAL PROPERTIES OF POLYMERS

Polymer Sample	Density ρ (kg/m^3)	γ_{SV} (mJ/m^2)	Particle Size Range D (μm)
Teflon No.6 PTFE	2000	20.1	500-600
Teflon Grade 1 PTFE	2000	20.1	200-400
Polyvinylidene Fluoride PVenF	1380	25.0	3-30
Polyvinyl Fluoride PVF	1740	28.0	2-35
Polyethylene PE high density	960	31.0	30-120
Polymethyl Methacrylate PMMA	1118	39.0	30-200
Nylon 6,6 PA 6,6	1080	40.8	60-250
Polysulfone PSO	1240	43.1	10-100
Acetal AC	1430	46.1	20-200

TABLE 3. PHYSICAL PROPERTIES OF THE MATRIX MATERIALS FOR FREEZING FRONT EXPERIMENTS

Substance	Density ρ_L (kg/m^3)	Viscosity μ ($N \cdot s/m^2$)	Specific Heat C_p ($kJ/kg \cdot K$)	Thermal Conductivity k_p ($J/m \cdot s \cdot K$)	Surface Tension, γ_{LV} at melting point (mJ/m^2)	Surface Tension, γ_{SV} at melting point (mJ/m^2)
Thymol	925	0.00397	2.370	0.1298	29.9 at 51.5°C	29.4 at 51.5°C
Benzophenone	1146	0.00516	1.856	-	39.9 at 48.0°C	34.5 at 48.0°C
Water/ice	999.8	0.001787	4.2177	0.5610	75.6 at 0°C	80.2 at 0°C

TABLE 4. PHYSICAL PROPERTIES OF COMPONENTS OF SOLVENT PAIRS USED SEDIMENTATION VOLUME, V_{sed}, MEASUREMENTS

Solvent Pairs for V_{sed} Experiments	1. Component			2. Component			γ_{LV} Range for V_{sed}
	γ_{LV} (mJ/m^2)	ρ_{20} (kg/m^3)	b.p. °C	γ_{LV} (mJ/m^2)	ρ_{20} (kg/m^3)	b.p. °C	(mJ/m^2)
Diethylether/Tetralin	16.4	715	34.6	35.3	975	207	16.4-35.3
n-Hexane/Cyclohexanone	19.7	659	69.0	34.8	947	155	19.7-34.8
n-Octane/Decalin	21.7	703	126.0	32.3	896	189	21.7-32.3
Acetone/Ethylene Glycol	22.6	791	56.0	48.0	1113	197	22.6-48.0
Methanol/1,2 Propandiol	23.5	791	64.6	35.9	1036	187	23.5-35.9
Methanol/Ethylene Glycol	23.5	791	64.6	48.0	1113	197	23.5-48.0
Methanol/Thiodiethanol	23.5	791	64.6	52.5	1221	165	23.5-52.5
Methanol/Formamide	23.5	791	64.6	59.9	1134	210	23.5-59.9
Methanol/Water	23.5	791	64.6	72.7	998	100	23.5-72.7
n-Propanol/DMSO	24.4	804	97.0	44.5	1101	189	24.4-44.5
n-Propanol/ Thiodiethanol	24.4	804	97.0	52.5	1221	165	24.4-52.5
n-Propanol/Formamide	24.4	804	97.0	59.9	1134	210	24.4-59.9
n-Propanol/Water	24.4	804	97.0	72.7	998	100	24.4-72.7
Cyclohexane/Decalin	24.9	779	81.0	32.3	896	189	24.4-32.3
Propionic Acid/Water	26.9	993	141.0	72.7	998	100	26.9-72.7
Benzene/Chlorobenzene	28.9	874	80.2	33.6	1106	132	28.9-33.6
Benzene/1,2,4 Tri-Chlorobenzene	28.9	874	80.2	39.7	1454	214	28.9-39.7

TABLE 5. POLYMER SUBSTRATES USED IN THE COAL ADHESION EXPERIMENTS

Polymer	Source	Preparation	Contact Angle θ with H_2O (degree)	Surface Tension γ_{SV} (mJ/m^2)
Low Density Polyethylene LDPE	Commercial Plastics Toronto, Canada	Heat Press	84±4	32.5
Sulfonated Polystyrene SPS	Central Research Lab. Dow Chemical Co.	Film	24±3	66.7

TABLE 6. CRITICAL VELOCITY, V_c, FREE ENERGY OF ADHESION, ΔF^{adh}, PARTICLE SURFACE TENSION, γ_{PV} AND CONTACT ANGLE, θ, VALUES FOR COAL NO.1 AND CNRL #1 SAMPLES; MATRIX: THYMOL

SAMPLE	PARTICLE DIAMETER D (μm)	CRITICAL VELOCITY V_c ($\mu m/sec$)	ΔF^{adh} (mJ/m^2)	at 51.5°C γ_{PV} (mJ/m^2)	at 51.5°C θ (degree)	at 20°C γ_{PV} (mJ/m^2)	at 20°C θ (degree)
Coal No. 1	15	5.00+1.40	0.046+0.009	33.3+0.7	83.2+1.0	35.4+0.7	79.9+1.0
	30	3.70+1.00	0.052+0.010	33.7+0.7	82.7+1.7	35.7+0.7	79.4+1.2
	45	3.10+0.70	0.056+0.009	34.0+0.7	82.2+1.1	36.0+0.7	78.9+1.1
CNRL #1	15	6.80+0.75	0.057+0.004	34.0+0.3	82.1+0.5	36.1+0.3	78.8+0.5
	30	3.10+0.75	0.047+0.008	33.3+0.6	83.2+0.9	35.4+0.6	80.0+0.9
	45	2.55+0.70	0.050+0.009	33.5+0.7	82.9+1.0	35.6+0.7	79.6+1.0

TABLE 7. CRITICAL VELOCITY, V_c, FREE ENERGY OF ADHESION, ΔF^{adh}, PARTICLE SURFACE TENSION, γ_{PV} AND CONTACT ANGLE, θ, VALUES FOR CNRL #2 AND CNRL #3 COAL SAMPLES; MATRIX: THYMOL

SAMPLE	PARTICLE DIAMETER D (μm)	CRITICAL VELOCITY V_c (μm/sec)	ΔF^{adh} (mJ/m^2)	at 51.5°C		at 20°C	
				γ_{PV} (mJ/m^2)	θ (degree)	γ_{PV} (mJ/m^2)	θ (degree)
CNRL #2	15	5.60+1.10	0.049+0.007	33.5+0.5	83.0+0.8	35.5+0.5	80.5+0.8
	30	4.15+0.85	0.056+0.008	34.0+0.6	82.2+0.9	36.0+0.6	78.9+0.9
	45	3.65+0.75	0.063+0.009	34.5+0.7	81.4+1.1	36.5+0.7	78.1+1.1
	60	3.30+0.75	0.067+0.010	34.8+0.7	80.9+1.2	36.8+0.7	77.6+1.2
CNRL #3	15	9.00+2.00	0.069+0.011	34.9+0.8	80.7+1.3	37.0+0.8	77.4+1.3
	30	6.40+1.75	0.077+0.014	35.5+1.0	79.8+1.6	37.6+1.0	76.4+1.0
	45	5.45+1.60	0.084+1.017	36.0+1.2	78.9+2.0	38.1+1.2	75.6+2.0
	60	5.00+1.60	0.091+0.020	36.5+1.5	78.1+2.3	38.6+1.5	74.8+2.3

TABLE 8. CRITICAL VELOCITY, V_c, FREE ENERGY OF ADHESION, ΔF^{adh}, PARTICLE SURFACE TENSION, γ_{PV} AND CONTACT ANGLE, θ, VALUES FOR DEVCO METALLURGICAL COAL; MATRIX: THYMOL

PARTICLE DIAMETER D (μm)	CRITICAL VELOCITY V_c (μm/sec)	ΔF^{adh} (mJ/m^2)	at 51.5°C		at 20°C	
			γ_{PV_2} (mJ/m^2)	ϑ (degree)	γ_{PV_2} (mJ/m^2)	θ (degree)
15	6.70+1.60	0.055+0.009	33.9+0.6	82.3+1.0	36.0+0.6	79.0+1.0
30	5.40+1.40	0.067+0.012	34.8+0.8	80.9+1.4	36.8+0.8	77.6+1.4
45	4.60+1.20	0.073+0.013	35.2+0.9	80.2+1.5	37.3+0.9	76.9+1.5
60	4.05+1.10	0.077+0.014	35.5+1.0	79.8+1.6	37.6+1.0	76.4+1.6
75	3.85+1.00	0.083+0.015	35.9+1.1	79.1+1.8	38.0+1.1	75.8+1.8
90	3.75+1.00	0.089+0.016	36.4+1.2	78.4+1.9	38.4+1.2	75.1+1.9
120	3.70+0.70	0.101+0.016	37.2+0.9	77.0+1.6	39.3+0.9	73.6+1.6
150	3.60+0.70	0.110+0.016	37.9+1.1	75.9+1.8	40.0+1.1	72.6+1.8
180	3.45+0.70	0.117+0.016	38.4+1.2	75.2+2.0	40.5+1.2	71.7+2.0
210	3.30+0.70	0.122+0.018	38.8+1.3	74.4+2.1	40.9+1.3	71.0+2.1
240	3.20+0.70	0.128+0.019	39.2+1.3	74.1+2.3	41.3+1.4	70.4+2.3
270	3.05+0.70	0.131+0.021	39.4+1.5	73.4+2.5	41.5+1.5	70.0+2.5
300	2.95+0.70	0.135+0.022	39.7+1.6	72.9+2.6	41.8+1.6	69.5+2.6

TABLE 9. CRITICAL VELOCITY, V_c, FREE ENERGY OF ADHESION, ΔF^{adh}, PARTICLE SURFACE TENSION, γ_{PV} AND CONTACT ANGLE, θ, VALUES FOR MINTO R.O.M. COAL; MATRIX: THYMOL

PARTICLE DIAMETER D (μm)	CRITICAL VELOCITY V_c (μm/sec)	ΔF^{adh} (mJ/m^2)	at 51.5°C γ_{PV} (mJ/m^2)	at 51.5°C θ (degree)	at 20°C γ_{PV} (mJ/m^2)	at 20°C θ (degree)
15	-	-	-	-	-	-
30	10.00+1.80	0.100+0.012	37.2+0.9	77.1+1.4	39.2+0.9	73.7+1.4
45	8.10+1.40	0.105+0.012	37.5+0.9	76.5+1.4	39.5+0.9	73.2+1.4
60	6.85+1.40	0.108+0.015	37.7+1.1	76.1+1.8	39.8+1.1	72.8+1.8
75	5.80+1.40	0.107+0.018	37.3+1.3	76.3+2.1	39.7+1.3	72.9+2.1
90	5.10+1.20	0.107+0.017	37.7+1.2	76.3+2.0	39.7+1.2	72.9+2.0
120	4.15+1.00	0.107+1.018	37.7+1.3	76.3+2.1	39.7+1.3	72.9+2.1
150	3.65+0.80	0.109+1.016	37.8+1.2	76.0+1.9	39.9+1.2	72.7+1.9
180	3.35+1.80	0.113+0.018	38.1+1.3	75.6+2.1	40.1+1.3	72.2+2.1
210	3.30+0.80	0.120+0.020	38.6+1.5	74.7+2.4	40.7+1.5	71.4+2.4
240	3.30+0.80	0.128+0.021	39.2+1.5	73.8+2.5	41.2+1.5	70.4+2.5
270	3.30+0.80	0.136+0.023	39.8+1.7	72.8+2.8	41.8+1.7	69.4+2.8
300	3.25+0.80	0.141+0.024	40.1+1.7	72.2+2.9	42.2+1.7	68.8+2.9

TABLE 10. PARTICLE SURFACE TENSION, γ_{PV}, FOR VARIOUS PARTICLE DIAMETERS, D, FOR THE -400 MESH FRACTIONS OF VARIOUS COAL SAMPLES AT 20°C FROM FREEZING FRONT EXPERIMENTS

MATRIX: THYMOL

SAMPLE -400 MESH	D (μm)	γ_{PV} AT 20°C (mJ/m²)	MEAN γ_{PV} (mJ/m²)
COAL NO.1	15	35.4	35.7
	30	35.7	
	45	36.0	
CNRL #1	15	36.1	35.7
	30	35.4	
	45	35.6	
CNRL #2	15	35.5	36.0
	30	36.0	
	45	36.5	
CNRL #3	15	36.5	37.6
	30	37.6	
	45	38.1	
DEVCO Metallurgical	15	36.0	36.7
	30	36.8	
	45	37.3	
MINTO R.O.M.	15	-	39.4
	30	39.2	
	45	39.6	

TABLE 11. SURFACE CHARACTERISTICS OF DEVCO COAL AT 51.5°C "AS RECEIVED" AND AGED SAMPLES

MATRIX: THYMOL

Coal Sample DEVCO	Diameter D (μm)	Critical Velocity V_c (μm/sec)	ΔF^{adh} (mJ/m²)	γ_{PV} (mJ/m²)
"As Received"	60	4.05±1.10	0.077±0.014	35.5±1.0
	90	3.75±1.00	0.089±0.016	36.4±1.2
	120	3.70±0.70	0.101±0.016	37.2±0.9
	150	3.60±0.70	0.110±0.016	37.9±1.1
	180	3.45±0.70	0.117±0.016	38.4±1.2
	210	3.30±0.70	0.122±0.018	38.8±1.3
	240	3.20±0.70	0.128±0.019	39.2±1.3
Aged at Room Temperature in Air	60	15.70±3.30	0.216±0.031	45.6±1.8
	90	14.60±2.70	0.225±0.029	46.3±1.8
	120	13.10±1.95	0.240±0.027	47.4±1.6
	150	12.10±1.45	0.253±0.025	48.3±1.5
	180	11.30±1.15	0.264±0.024	49.1±1.4
	210	10.70±0.90	0.274±0.023	49.8±1.3
	240	10.40±0.70	0.287±0.022	50.7±1.2
Aged at Room Temperature in N_2	60	12.70±1.70	0.168±0.014	42.1±0.8
	90	11.00±1.40	0.185±0.018	44.3±1.0
	120	10.00±1.20	0.199±0.020	44.4±1.2
	150	9.30±1.00	0.211±0.021	45.3±1.2
	180	8.70±0.80	0.221±0.021	46.0±1.2
	210	8.50±0.60	0.234±0.020	46.9±1.2
	240	8.30±0.50	0.246±0.020	47.8±1.2
Aged Near 0°C in Air	60	13.00±3.50	0.171±0.040	42.4±1.9
	90	10.10±2.80	0.174±0.033	42.6±1.4
	120	9.20±2.20	0.188±0.031	43.6±1.2
	150	8.90±2.10	0.206±0.033	44.9±1.4
	180	8.80±1.90	0.222±0.033	46.1±1.4
	210	8.80±1.90	0.239±0.036	47.3±1.5
	240	8.70±1.90	0.254±0.038	48.4±1.6
Aged Near 0°C in N_2	60	10.30±2.30	0.145±0.022	40.5±1.6
	90	8.10±1.90	0.150±0.024	40.8±1.7
	120	7.30±1.50	0.160±0.023	41.6±1.7
	150	6.80±1.30	0.171±0.022	42.4±1.6
	180	6.50±1.10	0.181±0.021	43.0±1.5
	210	6.30±0.90	0.191±0.020	43.8±1.4
	240	6.20±0.90	0.202±0.020	44.6±1.4

TABLE 12. SURFACE CHARACTERISTICS OF DEVCO COAL

AT 51.5°C AGED/OVEN-DRIED SAMPLES

MATRIX: THYMOL

Coal Sample DEVCO	Diameter D (μm)	Critical Velocity V_c (μm/sec)	ΔF^{adh} (mJ/m^2)	γ_{PV} (mJ/m^2)
Aged/Dried at Room Temperature in Air	60	16.90±3.10	0.204±0.026	44.8±1.9
	90	14.05±2.50	0.219±0.027	45.8±1.9
	120	11.85±2.20	0.224±0.029	46.2±1.1
	150	10.30±2.00	0.227±0.030	46.4±1.2
	180	9.35±1.80	0.232±0.031	46.8±1.2
	210	8.60±1.70	0.236±0.032	47.1±1.3
	240	8.05±1.70	0.240±0.032	47.4±1.5
Aged/Dried at Room Temperature in N_2	60	11.25±2.90	0.155±0.027	41.2±2.0
	90	9.45±2.50	0.169±0.030	42.2±1.2
	120	8.50±2.30	0.178±0.033	42.9±1.4
	150	8.00±2.10	0.191±0.034	43.8±1.5
	180	7.80±2.00	0.205±0.036	44.8±1.6
	210	7.60±1.90	0.217±0.037	45.7±1.7
	240	7.50±1.80	0.229±0.038	46.6±1.7
Aged/Dried Near 0°C in Air	60	15.40±4.60	0.192±0.039	43.9±2.8
	90	12.60±3.20	0.203±0.035	44.7±2.5
	120	11.10±2.40	0.214±0.032	45.5±2.3
	150	10.00±2.10	0.222±0.032	46.1±2.3
	180	9.40±1.90	0.233±0.032	45.9±2.3
	210	8.90±1.80	0.241±0.033	47.4±2.3
	240	8.65±1.60	0.250±0.032	48.3±2.3
Aged/Dried Near 0°C in N_2	60	15.50±2.50	0.192±0.032	43.9±1.2
	90	13.00±2.50	0.208±0.028	45.0±1.8
	120	11.00±2.50	0.213±0.026	45.4±1.3
	150	9.40±2.40	0.213±0.026	45.4±1.8
	180	8.25±2.25	0.213±0.026	45.4±1.8
	210	7.40±1.90	0.213±0.026	45.4±1.8
	240	6.65±1.55	0.211±0.025	45.3±1.7

TABLE 13. SURFACE CHARACTERISTICS OF DEVCO COAL

AT 51.5°C AGED/GLOW DISCHARGED SAMPLES

MATRIX: THYMOL

DEVCO Coal Aged at Room Temperature in Air	Diameter D (μm)	Critical Velocity V_c (μm/sec)	ΔF^{adh} (mJ/m²)	γ_{PV} (mJ/m²)
Aged/Glow Discharged for 30 min.	60	12.00±1.90	0.162±0.027	41.7±1.0
	90	10.30±1.50	0.177±0.029	42.8±1.1
	120	9.00±1.30	0.186±0.032	43.4±1.3
	150	7.90±1.05	0.189±0.034	43.7±1.4
	180	7.30±1.10	0.196±0.035	44.2±1.5
	210	6.80±0.80	0.201±0.032	44.5±1.4
	240	6.40±0.70	0.205±0.031	44.8±1.4
Aged/Glow Discharged for 2 hrs.	60	12.00±2.00	0.162±0.024	41.7±1.8
	90	10.05±1.70	0.174±0.032	42.6±1.3
	120	8.50±1.30	0.174±0.034	42.8±1.5
	150	7.20±1.30	0.177±0.038	42.8±1.5
	180	6.55±1.00	0.182±0.038	43.2±1.7
	210	6.10±0.70	0.186±0.032	43.4±1.7
	240	5.60±0.40	0.187±0.032	43.5±1.3

TABLE 14. PARTICLE SURFACE TENSION, γ_{PV}, OF DEVCO COAL AFTER VARIOUS AGING PROCESSES

Particle Diameter D (μm)	Particle Surface Tension, γ_{PV}, at 20°C (mJ/m^2)					
	"As Received"	Aged		Aged/Dried		Aged/Glow Discharged
		in air	in N_2	in air	in N_2	in air
		Stored at Room Temperature for 3 months				
60	37.6	47.6	44.2	46.8	43.2	43.7
90	38.4	48.3	45.4	47.9	44.3	44.8
120	39.3	49.4	46.4	48.3	44.9	45.5
150	40.0	50.3	47.3	48.5	45.9	45.7
180	40.5	51.1	48.0	48.8	46.9	46.2
210	40.9	51.8	48.9	49.1	47.7	46.6
240	41.3	52.7	49.8	49.1	48.6	46.9
		Stored Near 0°C for 3 months				
60		44.4	42.5	45.9	45.9	
90		44.6	42.9	46.7	47.1	
120		45.6	43.6	47.5	47.5	
150		46.9	44.4	48.1	47.5	
180		48.1	45.1	48.9	47.5	
210		49.4	45.9	49.5	47.5	
240		50.4	46.7	50.3	47.5	

TABLE 15a. SURFACE TENSION γ_{LV}, OF LIQUID PAIRS AT 20°C

Concentration of 1st Component (Vol.%)	γ_{LV} (mJ/m²) at 20°C					
	Diethylether Tetralin	Hexane Cyclohexanone	Octane Decalin	Acetone Ethylene Glycol	Methanol 1,2 Propandiol	Methanol Ethylene Glycol
100	16.4	19.7	21.7	22.6	23.5	23.5
90	17.9	19.9				
80	19.1	20.7	23.0	24.9	25.1	26.1
70	20.1	21.5			26.5	27.8
60	21.2	22.2	25.1	26.7	27.7	29.7
50	22.7	23.2	26.1	28.2	29.1	32.1
40	24.4	24.3	27.1	30.2	30.4	34.6
30		26.1	28.4	32.7	32.3	37.5
20	28.5	28.0	29.6	36.3	33.4	43.0
15			30.0	38.6		
10	30.9	30.9	30.2	41.4	34.8	
5		32.7	30.8	44.2		
2.5		33.2		47.0		
0	35.0	34.8	32.3	48.0	35.9	48.0

TABLE 15b. SURFACE TENSION γ_{LV}, OF LIQUID PAIRS AT 20°C (Continued)

	γ_{LV} (mJ/m^2) at 20°C					
Concentration of 1st Component (Vol.%)	Methanol Thiodiethanol	Methanol Formamide	Methanol Water	n-Propanol DMSO	n-Propanol Thiodiethanol	n-Propanol Formamide
100	23.5	23.5	23.5	24.4	24.4	24.4
90			27.9			
80	26.0	26.9	31.8	26.1	26.4	27.0
70	27.7	29.5	36.3	26.9	27.6	27.9
60	29.1	31.1	38.7	28.5	28.8	28.9
50	31.5	33.9	44.0	29.9	30.5	30.6
40	34.4	36.7	47.2	31.7	32.2	32.0
30	37.9	40.5		33.4	35.0	34.4
20	42.2	44.9	49.9	36.9	37.9	38.1
15				38.2	39.5	41.8
10	48.0	50.9		39.3	40.6	44.0
5				41.7	47.1	51.2
2.5				42.0	50.0	54.5
0	52.5	59.5	72.0	44.5	52.5	59.9

TABLE 15c. SURFACE TENSION γ_{LV}, OF LIQUID PAIRS AT 20°C (Continued)

Concentration of 1st Component (Vol.%)	γ_{LV} (mJ/m²) at 20°C				
	n-Propanol Water	Cyclohexane Decalin	Propionic Acid/Water	Benzene Chlorobenzene	Benzene 1,2,4 Trichlorobenzene
100	24.4	24.9	26.9	28.9	28.9
90		25.7		29.1	30.0
80		26.0	29.6	29.4	30.8
70		27.0	30.7	30.0	31.7
60		27.7	31.8	31.0	32.8
50	25.9	28.0	32.8	31.6	33.1
40	27.0	28.7	34.0	32.2	34.5
30	27.7	29.5	35.4	32.4	35.8
20	30.3	30.4	38.0	33.0	37.0
15	33.9				
10	39.9	31.5	42.8	33.5	38.5
5	47.7				
2.5	53.0				
0	72.0	32.3	72.0	33.6	39.7

TABLE 16. SURFACE TENSION, γ_{LV}, OF VARIOUS SOLVENTS USED FOR THE SEDIMENTATION VOLUME, V_{sed}, MEASUREMENTS AT 20°C

Solvent	γ_{LV} at 20°C (mJ/m^2)
Bis (2-etoxy ethylether)	27.9
Bis (2-methoxy ethylether)	30.3
Decahydronaphthalene (Decalin)	32.3
Tetrahydronaphthalene (Tetralin)	35.3
Dipropylene Glycol	36.4
1,2 Propandiol	37.3
1,3 Butandiol	38.3
1,3 Propandiol	44.2
1,4 Butandiol	46.1

TABLE 17. SURFACE TENSION OF INDUSTRIAL OILS USED FOR SEDIMENTATION VOLUME, V_{sed}, MEASUREMENTS AT 20°C

Industrial Oil	γ_{LV} at 20°C (mJ/m^2)
MIBC	24.4
VARSOL	28.9
Fuel Oil No.2	30.0
Light Oil	31.6
Cresylic Acid	37.5

TABLE 18. SEDIMENTATION VOLUME, V_{sed}, EXTREMUM OBSERVED FOR PTFE AND PE AT SURFACE TENSION γ_{LV} OF VARIOUS SOLVENT PAIRS

Polymer	V_{sed} Extremum at γ_{LV} (mJ/m^2)		
	PTFE		PE
Solvent Pair	No.6	Grade 1	
Diethylether/Tetralin	19.1	20.1	26.1
n-Hexane/Cyclohexanone	21.4	21.4	28.4
Industrial Oils	-	-	30.0
Mean	20.3	20.8	28.2

TABLE 19. COMPARISON BETWEEN THE SURFACE TENSION, γ_{SV}, OF POLYMERS OBTAINED FROM CONTACT ANGLES AND FROM THE SEDIMENTATION VOLUME EXTREMUM

Polymer	θ_{H_2O} (degrees)	γ_{SV} Eq. of State (mJ/m^2)	V_{sed} Extremum at γ_{LV} (mJ/m^2)
Teflon No.6 PTFE	103.8±2	20.1	20.3
Teflon Grade 1 PTFE	103.8±2	20.1	20.8
Polyvinylidene Fluoride PVenF	95.5±2	25.0	36.5
Polyvinylfluoride PVF	90.7±2	28.0	34.7
Polyethylene PE high density	86±2	31.0	28.2
Polymethylmethacrylate PMMA	73±2	39.0	43.6
Nylon 6,6 PA 6,6	70±3	40.8	39.8
Polysulfone PSO	66±2	43.1	42.9
Acetal AC	61.5±1	46.1	47.0

TABLE 20. COMPARISON BETWEEN γ_{PV} VALUES OF COAL NO.1 (-400 MESH FRACTION) DETERMINED BY THE FREEZING FRONT TECHNIQUE AND BY SEDIMENTATION VOLUME MEASUREMENT AT 20°C

SOLVENT PAIRS	γ_{PV} (mJ/m^2) FROM V_{sed}	FROM V_c
n-Octane/Decalin	28.4	
Cyclohexane/Decalin	28.7	
Methanol/Thiodiethanol	31.5	
Methanol/Formamide	33.9	
Benzene/Chlorobenzene	32.4	35.7
Benzene/1,2,4,Trichlorobenzene	33.1	
Methanol/Ethylene Glycol	33.4	
Aceton/Ethylene Glycol	34.6	
n-Propanol/Water	34.9	
n-Propanol/DMSO	29.9	
Methanol/Water	31.8	
Industrial Oils	30.0	
MEAN	33.2	

TABLE 21. SEDIMENTATION VOLUME, V_{sed}, EXTREMUM FOR COALS AT SURFACE TENSION, γ_{LV}, OF VARIOUS SOLVENT PAIRS

Coal / Solvent Pair	V_{sed} Extremum at γ_{LV} (mJ/m^2)				
	CNRL #1	CNRL #2	CNRL #3	DEVCO	MINTO
n-Octane/Decalin	28.4	29.6	-	-	-
Industrial Oils	32.0	-	-	31.6	-
n-Propanol/Thiodiethanol	36.2	38.0	38.1	-	38.0
n-Propanol/Formamide	34.4	-	38.1	36.4	-
n-Propanol/Water	36.5	36.5	40.0	36.5	39.9
Propionic Acid/Water	31.9	32.8	-	34.0	-
Mean	34.6	35.8	38.7	35.6	39.0

TABLE 22. PARTICLE SURFACE TENSION, γ_{PV}, FOR FRACTIONS BELOW 400 MESH OF VARIOUS COAL SAMPLES AT 20°C

Sample -400 Mesh	γ_{PV} (mJ/m^2) From V_c	From V_{sed}
Coal No.1	35.7	33.2
CNRL #1	35.7	34.6
CNRL #2	36.0	35.8
CNRL #3	37.6	38.7
DEVCO	36.7	35.6
MINTO	39.4	39.0

TABLE 23. SEDIMENTATION VOLUME, V_{sed}, EXTREMUM FOR CLAYS AT SURFACE TENSION, γ_{LV}, OF VARIOUS SOLVENT PAIRS

Clay	V_{sed} Extremum at γ_{LV} (mJ/m^2)		
Solvent Pair	Kaolinite	Bentonite	Mica
Hexane/Cyclohexanone	32.7	32.7	-
Different Ethers and Diols	-	36.4	-
n-Propanol/DMSO	31.7	-	39.3
n-Propanol/Thiodiethanol	33.8	35.1	41.2
n-Propanol/Water	-	-	39.9
Mean	32.7	34.7	40.1

TABLE 24. SOLID/VAPOUR INTERFACIAL TENSION, γ_{SV}, OF COALS FROM DIRECT CONTACT ANGLE MEASUREMENTS AT 20°C USING THE SESSILE DROP TECHNIQUE

Coal Sample	θ (degrees)			γ_{SV} (mJ/m^2)			γ_{PV} (mJ/m^2)	
	Water	Ethylene Glycol	Glycerol	Water	Ethylene Glycol	Glycerol	From V_c	From V_{sed}
DEVCO	80	51	-	34.0	33.1	-	36.7	35.6
MINTO	86	58	75	30.3	29.8	31.3	39.4	39.0

TABLE 25. TEMPERATURE DEPENDENCE OF THE SURFACE TENSIONS, γ_{LV}, OF OILS

γ_{LV} (mJ/m^2)					
TEMPERATURE °C	VARSOL	No. 2 FUEL OIL	LEDUC CRUDE OIL	BACHEQUERO CRUDE	COAL TAR XYLENE 50:50
20	28.88+0.99	29.95+1.16	30.95+2.28	34.61+0.28	35.30+0.46
30	27.89+0.96	28.96+0.93	30.29+1.91	33.80+0.49	34.40+0.41
40	26.87+0.83	27.98+0.67	29.63+1.55	33.17+0.58	33.50+0.53
50	25.88+0.78	27.02+0.52	29.00+1.19	32.47+0.38	32.53+0.42
60	24.86+0.78	26.04+0.28	28.31+0.92	31.69+0.17	31.61+0.36
70	23.84+0.66	25.03+0.09	27.60+0.61	30.98+0.00	30.65+0.41
80	22.85+0.54	24.04+0.19	26.95+0.28	30.30+0.05	29.72+0.36
90	21.81+0.48	23.05+0.42	26.30+0.00	29.56+0.21	28.76+0.39

TABLE 26. TEMPERATURE COEFFICIENTS OF THE SURFACE TENSION, $\frac{d\gamma_{LV}}{dT}$, of OILS

OIL SAMPLE	$\frac{d\gamma_{LV}}{dT}$ ($mJ/m^2.^oC$)
VARSOL	0.101±0.038
No. 2 FUEL OIL	0.099±0.024
LEDUC CRUDE OIL	0.066±0.027
BACHEQUERO CRUDE	0.071±0.021
COAL TAR/XYLENE 50:50 wt/w%	0.093±0.016

TABLE 27. SPECIFIC HEAT, C_p, OF COAL SAMPLES, AS A FUNCTION OF TEMPERATURE

^oK	C_p kJ/kg.K					
	Coal No.1 -400	CNRL #1 -400	CNRL #2 -400	CNRL #3 -400	DEVCO as mined bulk	MINTO as mined bulk
290	0.96+0.10	0.95+0.09	0.96+0.05	0.94+0.10	0.98+0.04	0.93+0.04
300	1.03+0.06	1.01+0.09	1.01+0.06	1.00+0.11	1.07+0.03	1.01+0.03
310	1.09+0.05	1.06+0.09	1.06+0.07	1.06+0.09	1.12+0.01	1.06+0.01
320	1.14+0.08	1.09+0.10	1.10+0.05	1.07+0.13	1.14+0.02	1.11+0.02
330	1.15+0.11	1.08+0.10	1.09+0.11	1.08+0.14	1.17+0.02	1.14+0.04
340	1.21+0.14	1.14+0.04	1.15+0.07	1.13+0.16	1.21+0.02	1.18+0.02
350	1.24+0.07	1.22+0.07	1.21+0.10	1.19+0.18	1.24+0.01	1.21+0.05
360	1.28+0.05	1.31+0.17	1.26+0.02	1.25+0.09	1.29+0.02	1.23+0.08

FLOW CHART OF DEVCO COAL FOR THE AGING STUDY

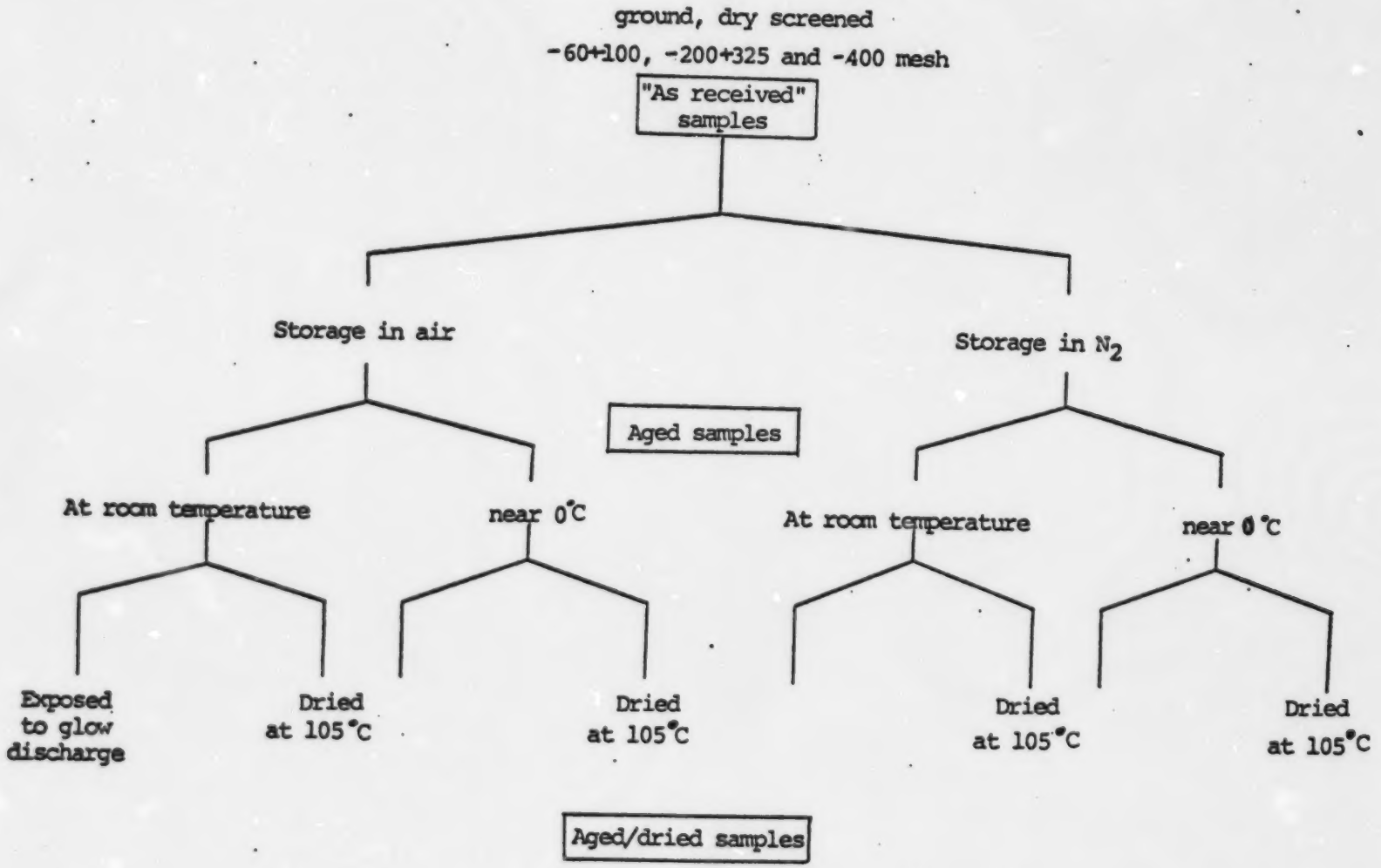

Figure 1. Flow Chart of DEVCO Coal for the Aging Study

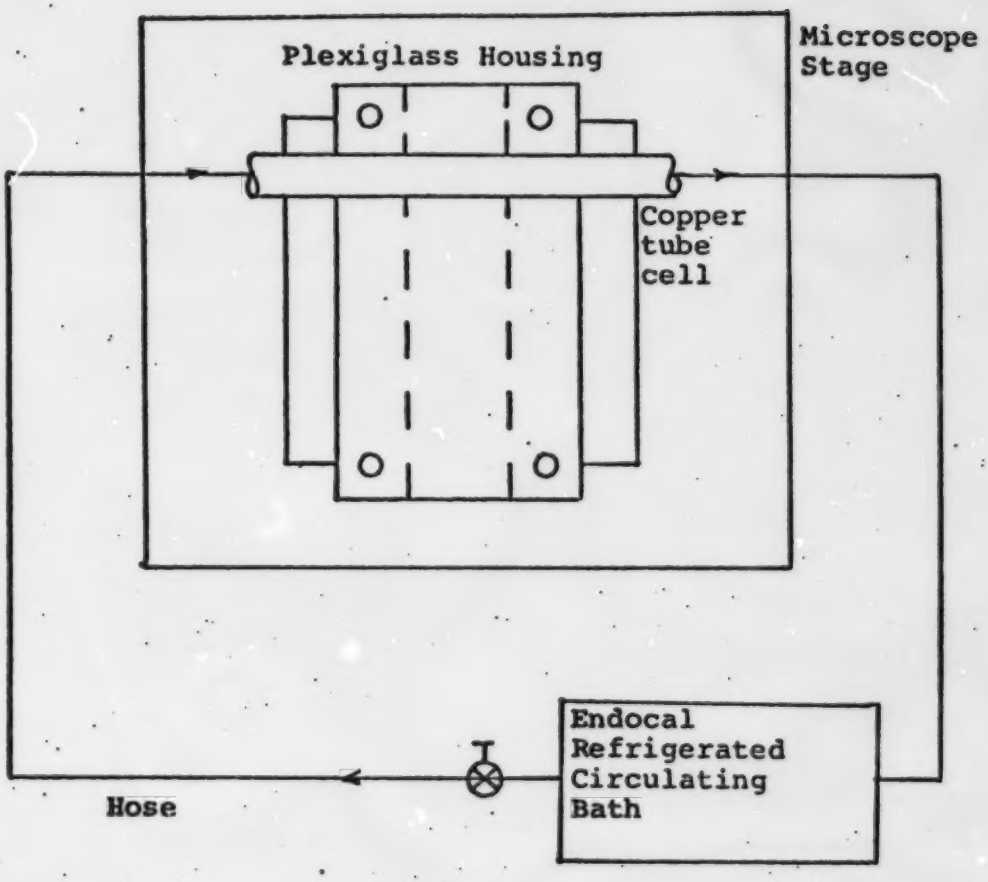

Figure 2a. Arrangement of Apparatus for Freezing Front Experiments with Liquid Droplets

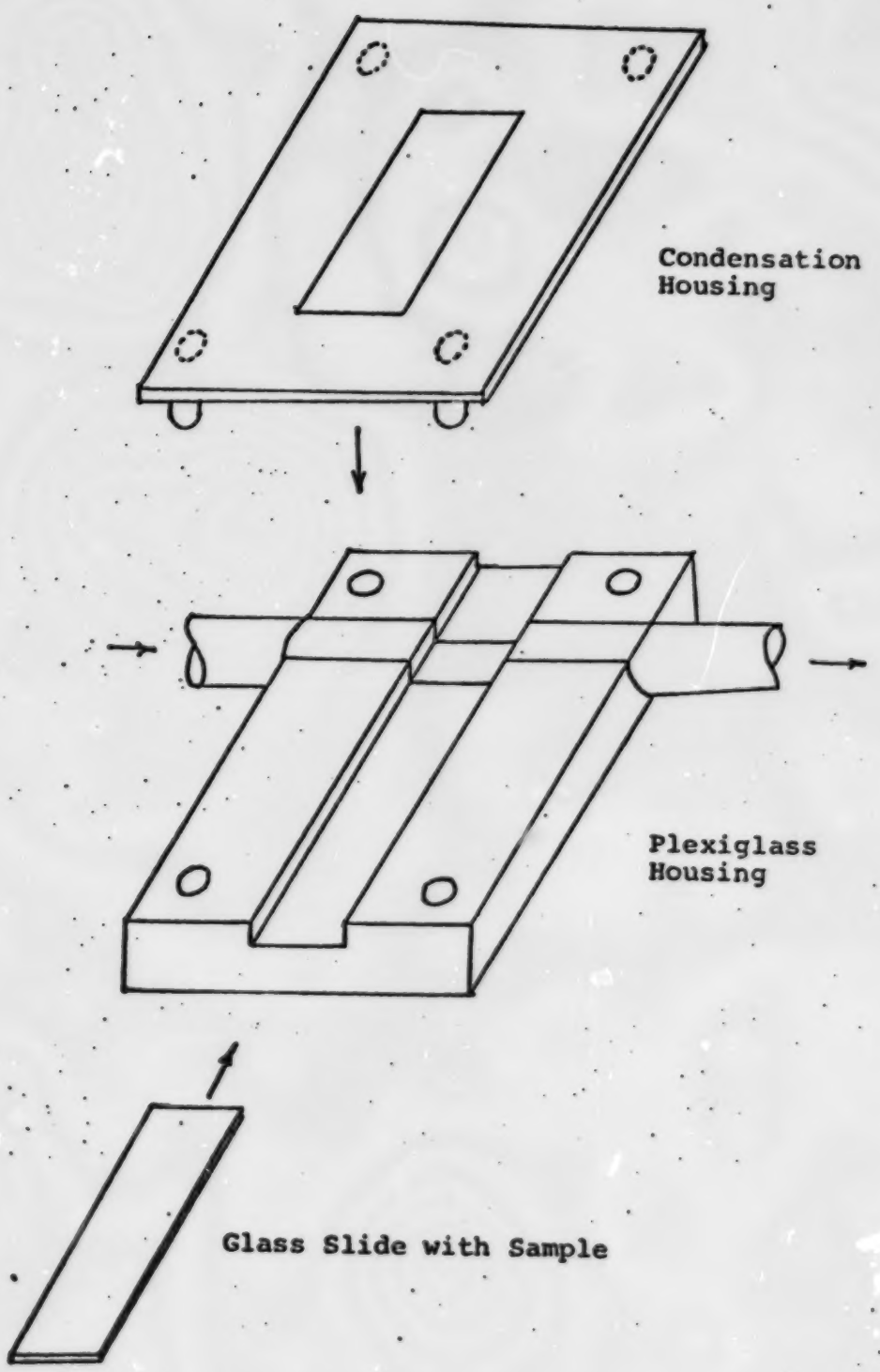

Figure 2b. Plexiglass Housing with Condensation Cover

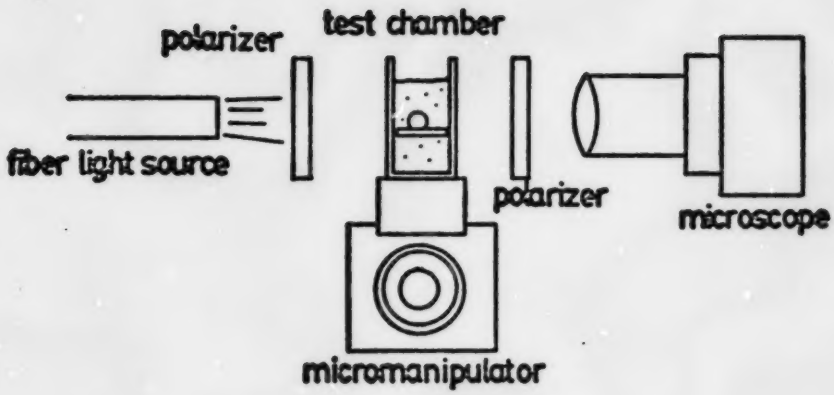

Figure 3. Schematic Diagram of Apparatus for Drop Profile Photography

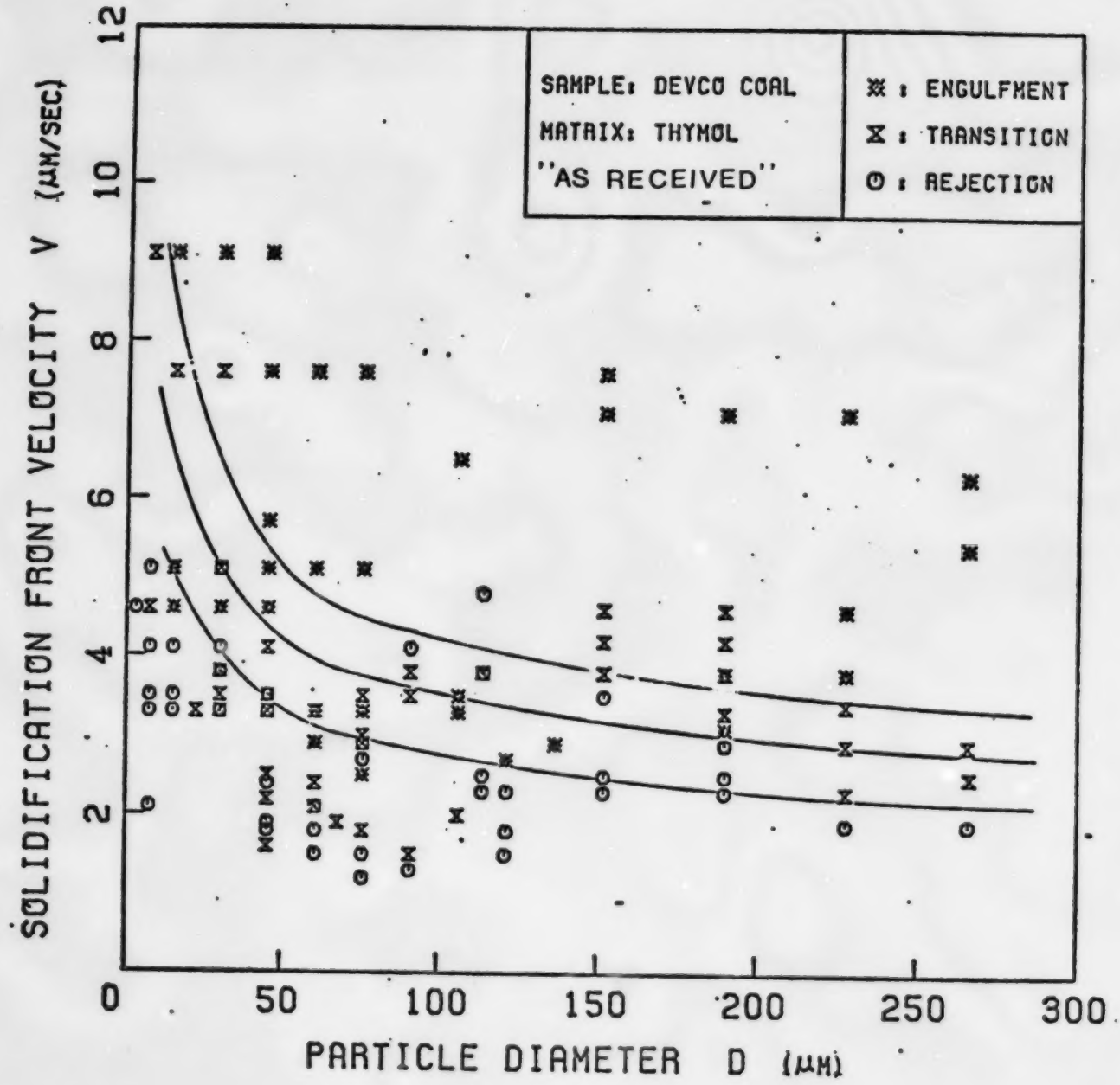

Figure 4. Solidification Front Velocity, V, versus Particle Diameter, D, for DEVCO Metallurgical Coal

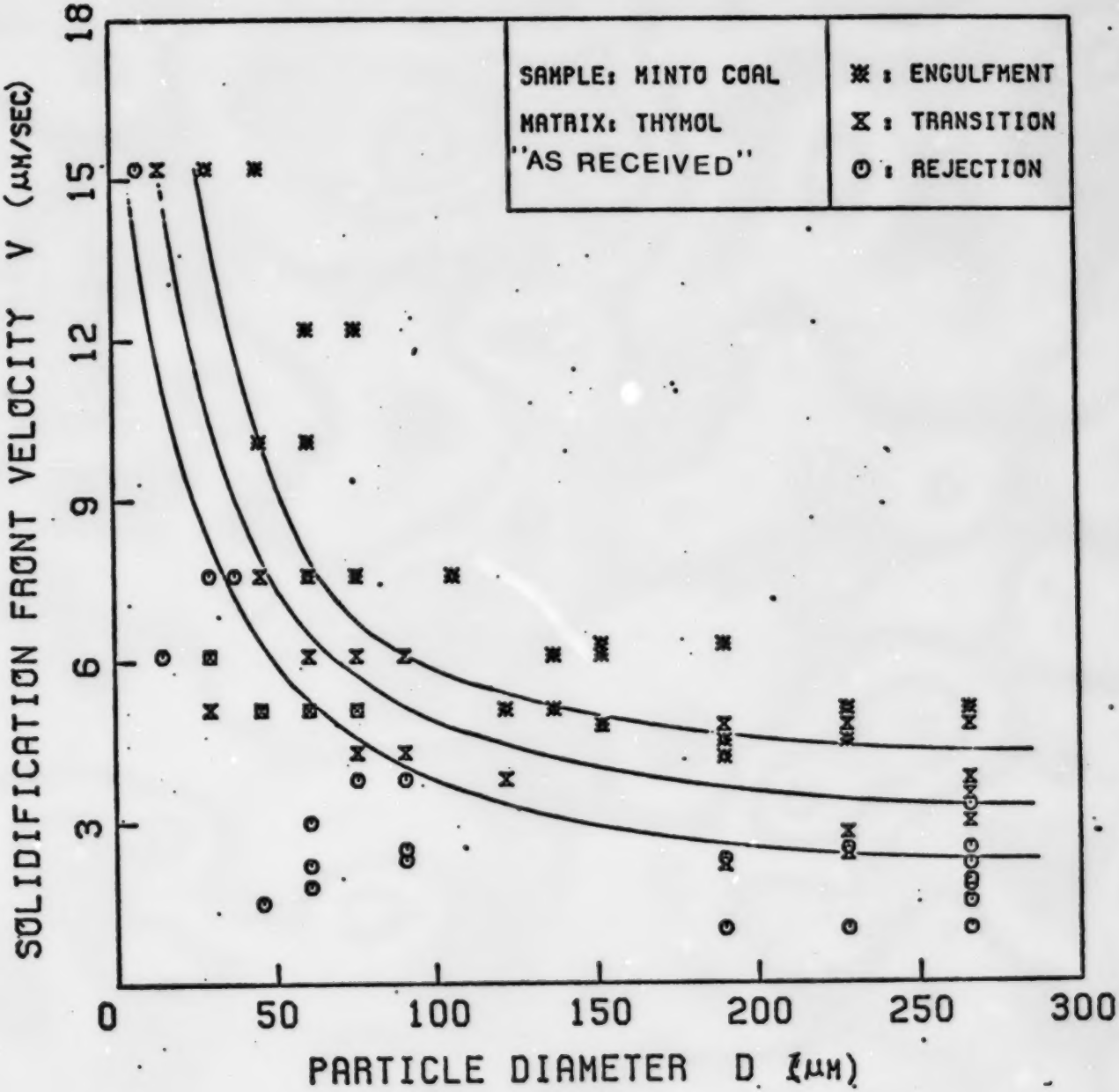

Figure 5. Solidification Front Velocity, V, versus Particle Diameter, D, for MINTO R.O.M. Coal

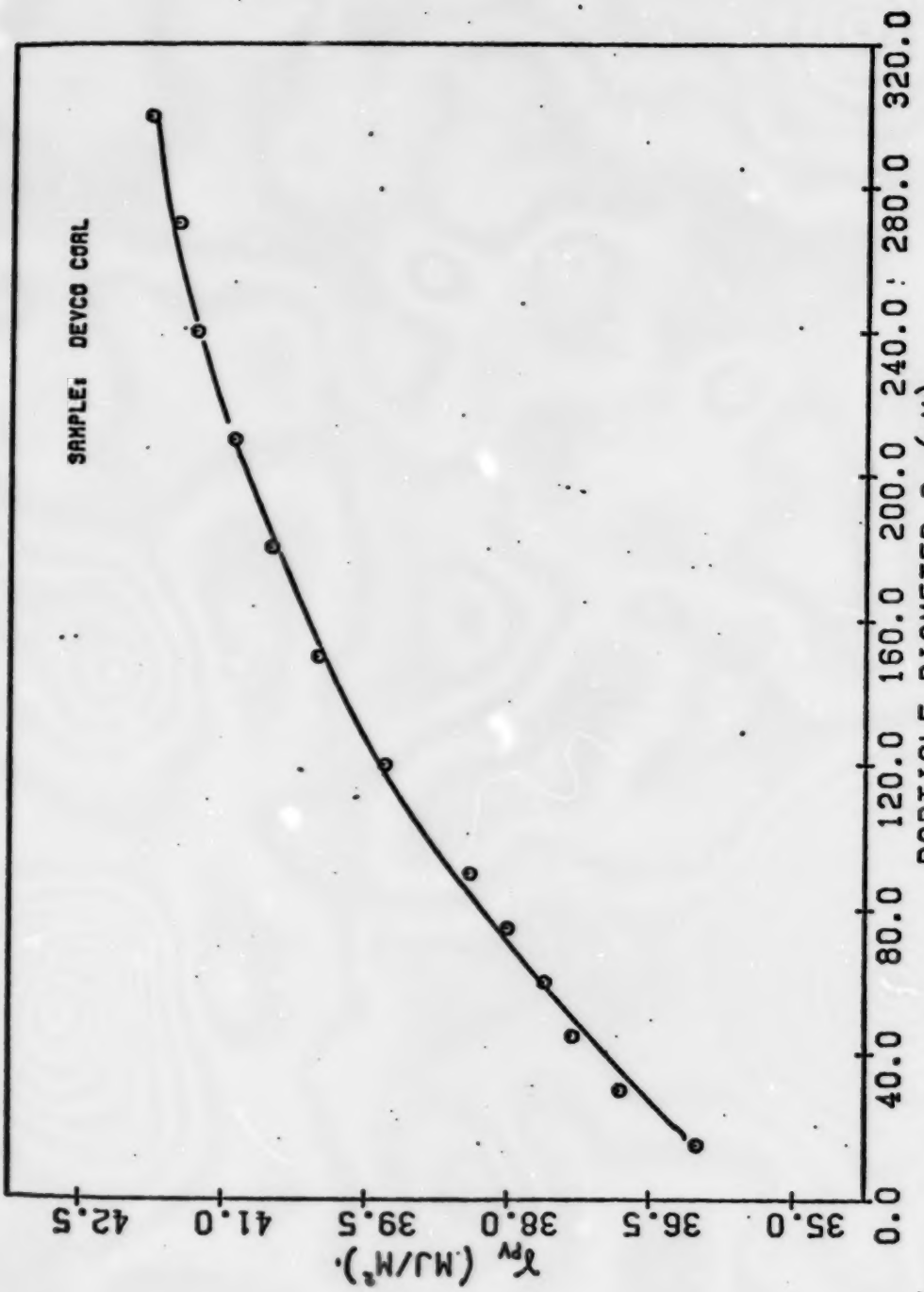

Figure 6a. Particle Surface Tension, γ_{pv}, as a Function of Particle Diameter, D, for DEVCO Coal "as received" at 20°C

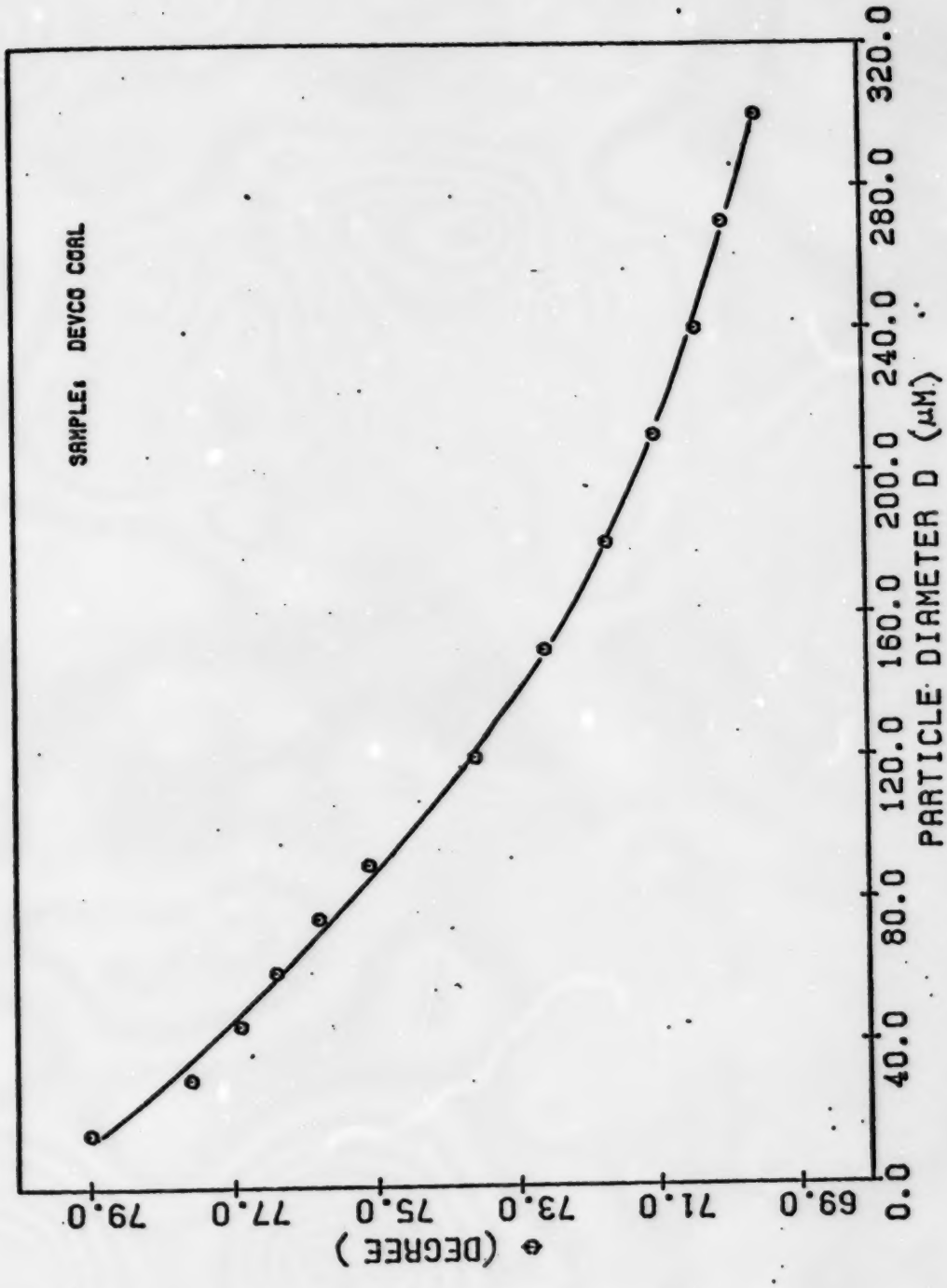

Figure 6b. Contact Angle, θ, as a Function of Particle Diameter, D, for DEVCO Coal "as received", at 20°C

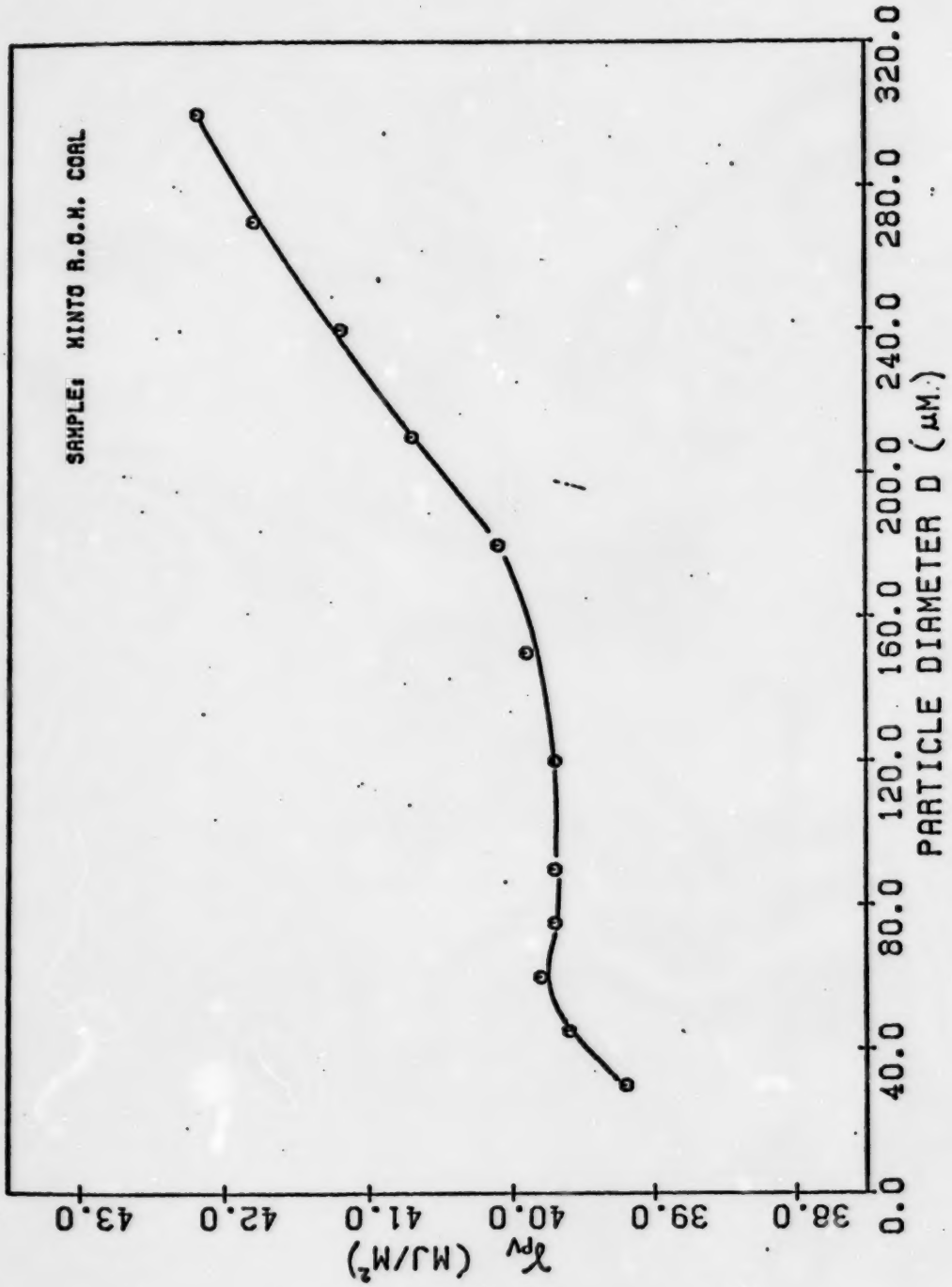

Figure 7a. Particle Surface Tension, γ_{PV}, as a Function of Particle Diameter, D, for MINTO Coal "as received", at 20°C

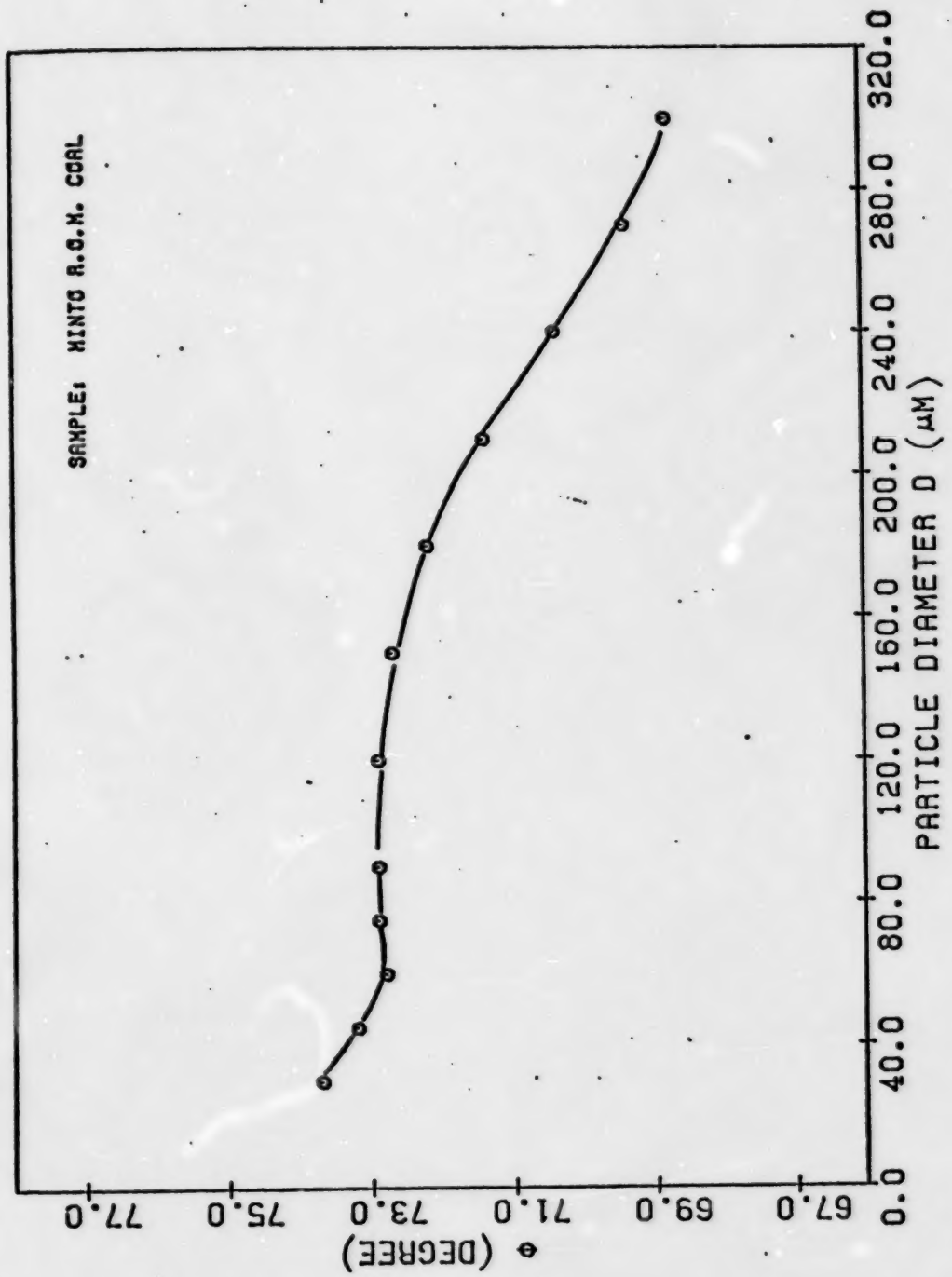

Figure 7b. Contact Angle, θ, as a Function of Particle Diameter, D, for MINTO Coal "as received", at 20°C

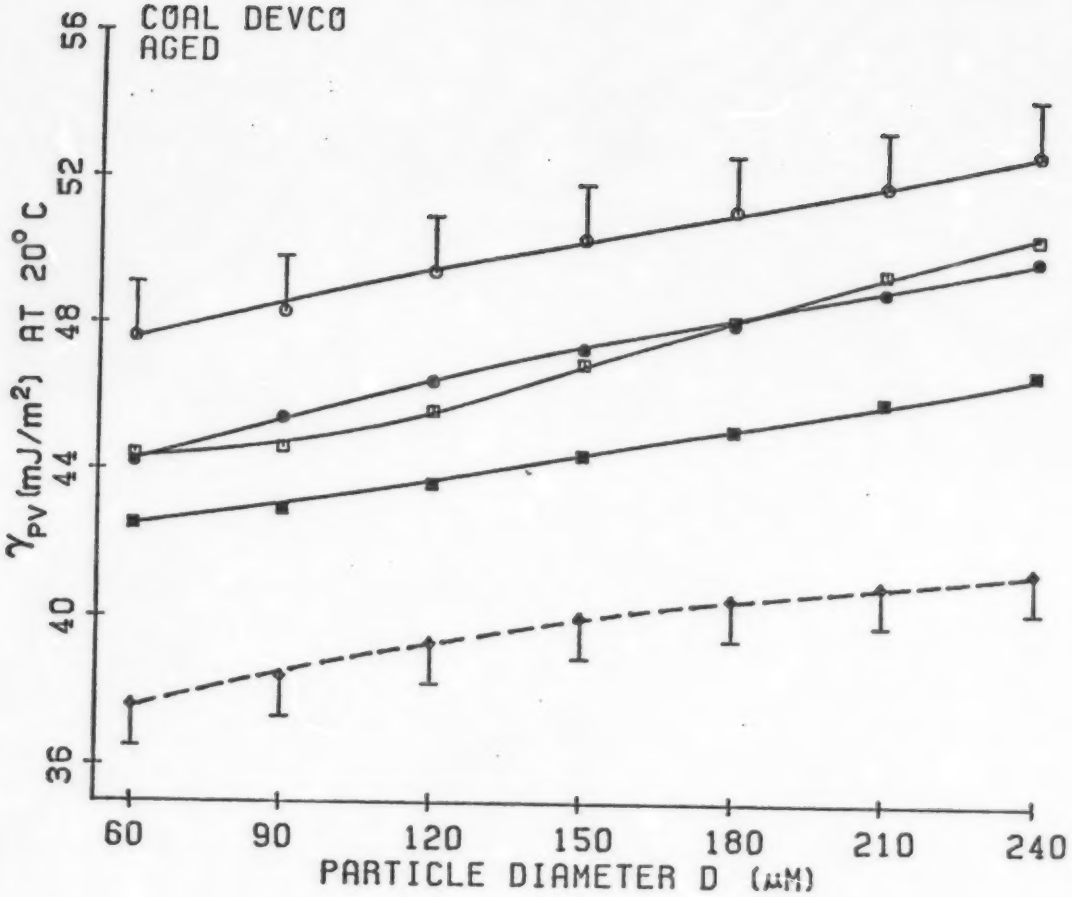

Figure 8. Particle Surface Tension, γ_{PV}, as a Function of Particle Diameter, D, for DEVCO Coal, Aged Samples;
◊ : "as received";
o: Aged at Room Temperature in Air;
●: Aged at Room Temperature in N_2;
□: Aged Near 0°C in Air;
■: Aged Near 0°C in N_2.

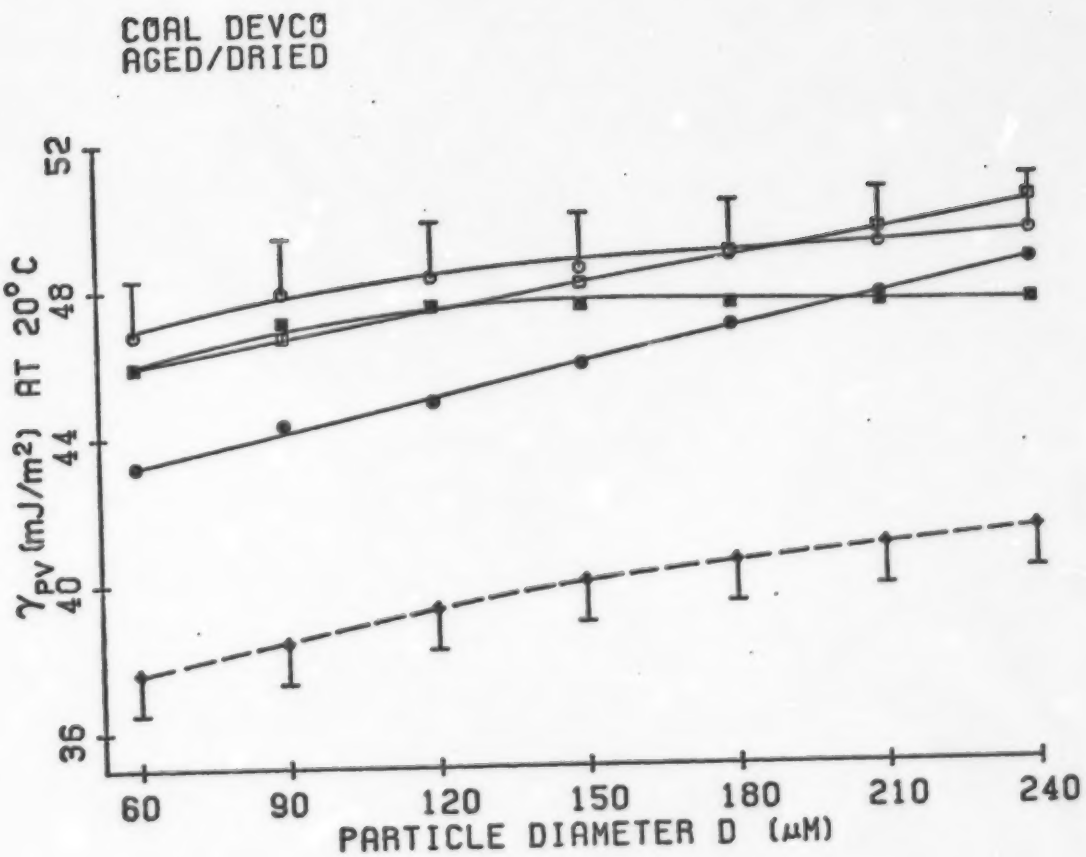

Figure 9. Particle Surface Tension, γ_{PV}, as a Function of Particle Diameter, D, for DEVCO Coal, Aged/Dried Samples;
◇ : "as received";
o: Aged at Room Temperature in Air;
●: Aged at Room Temperature in N_2;
□: Aged Near 0°C in Air;
■: Aged Near 0°C in N_2.

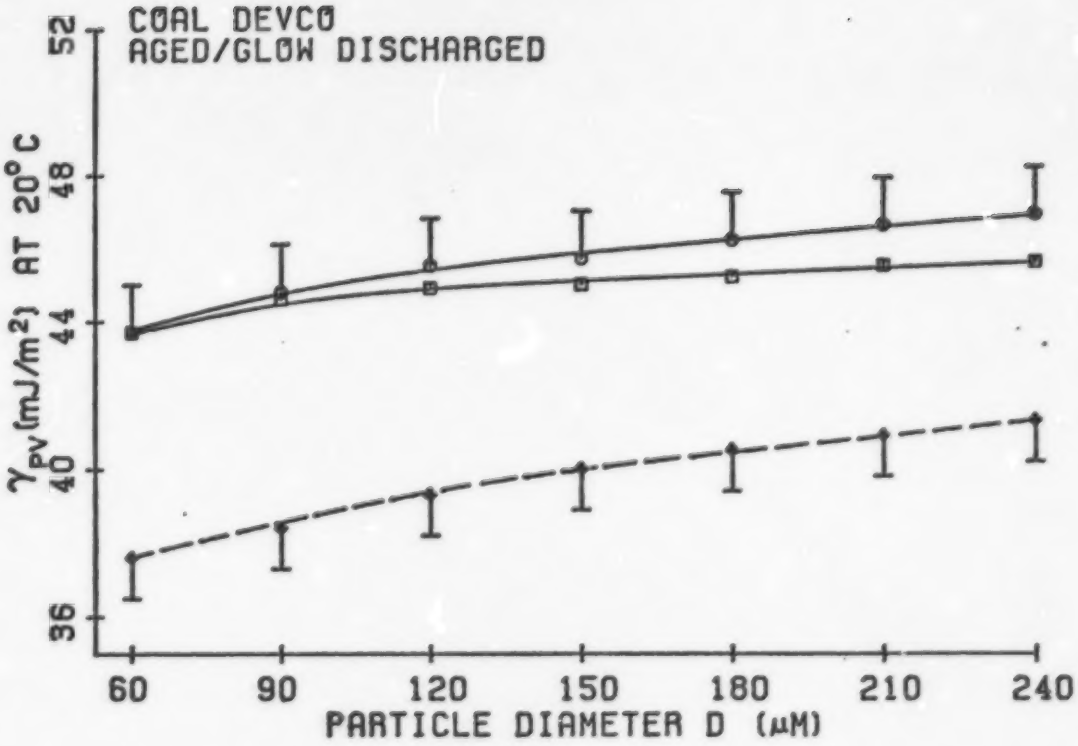

Figure 10. Particle Surface Tension, γ_{PV}, as a Function of Particle Diameter, D, for DEVCO Coal, Aged/Glow Discharged Samples;
◊ : "as received"; then
o: Glow Discharged for 30 Minutes;
□: Glow Discharged for 2 Hours.

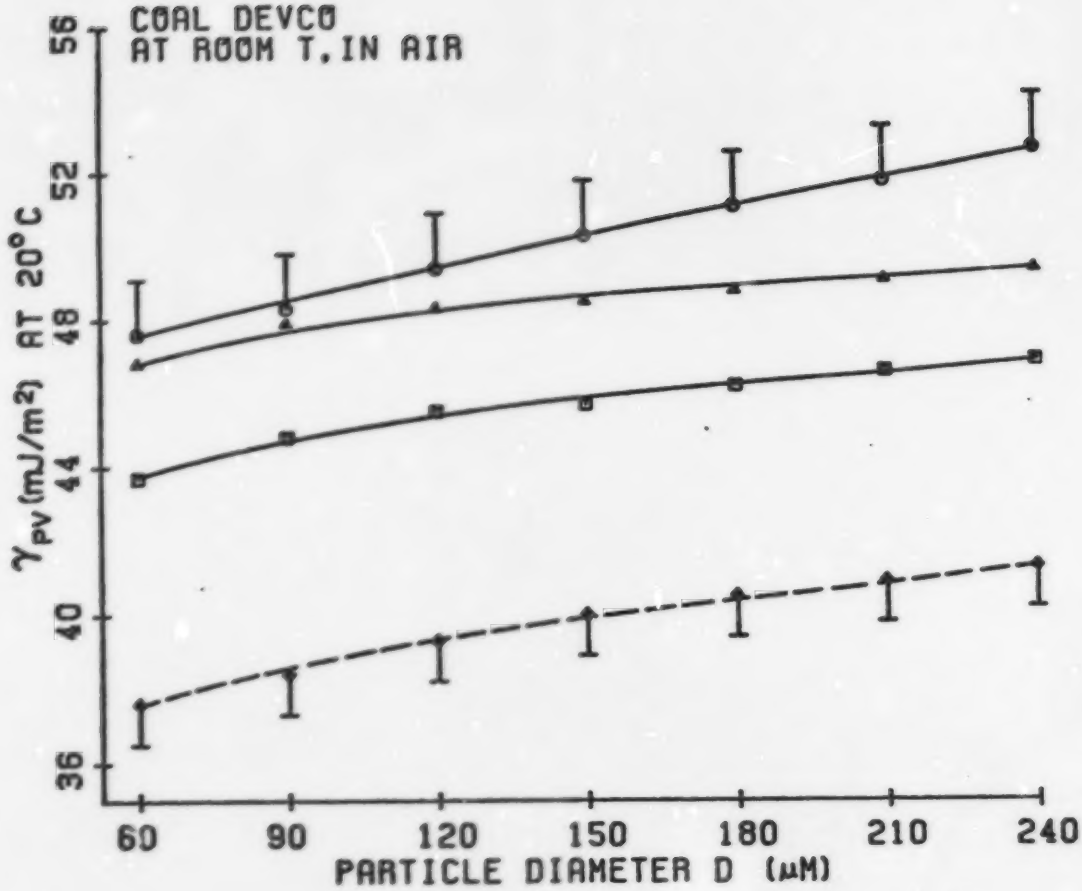

Figure 11. Particle Surface Tension, γ_{PV}, as a Function of Particle Diameter, D, for DEVCO Coal, Aged at Room Temperature in Air;

◊: "as received";
o: Aged;
Δ: Aged/Dried;
□: Aged/Glow Discharged.

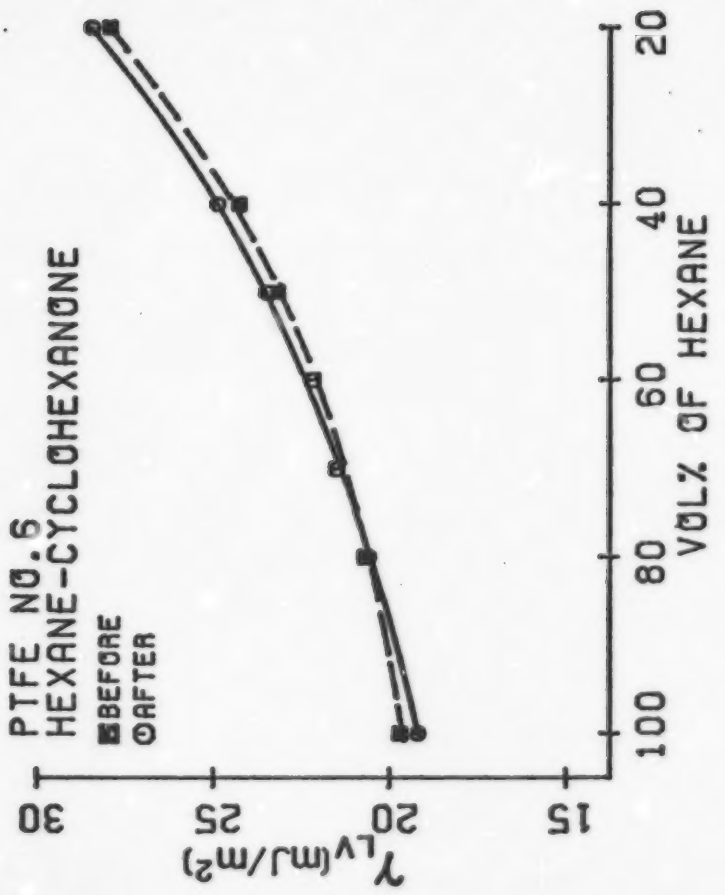

Figure 12. Surface Tension, γ_{LV}, of Liquid Medium (n-Hexane/Cyclohexanone) versus Concentration of n-Hexane Before and After the Sedimentation Volume, V_{sed}, Measurement; ■: Before; o: After

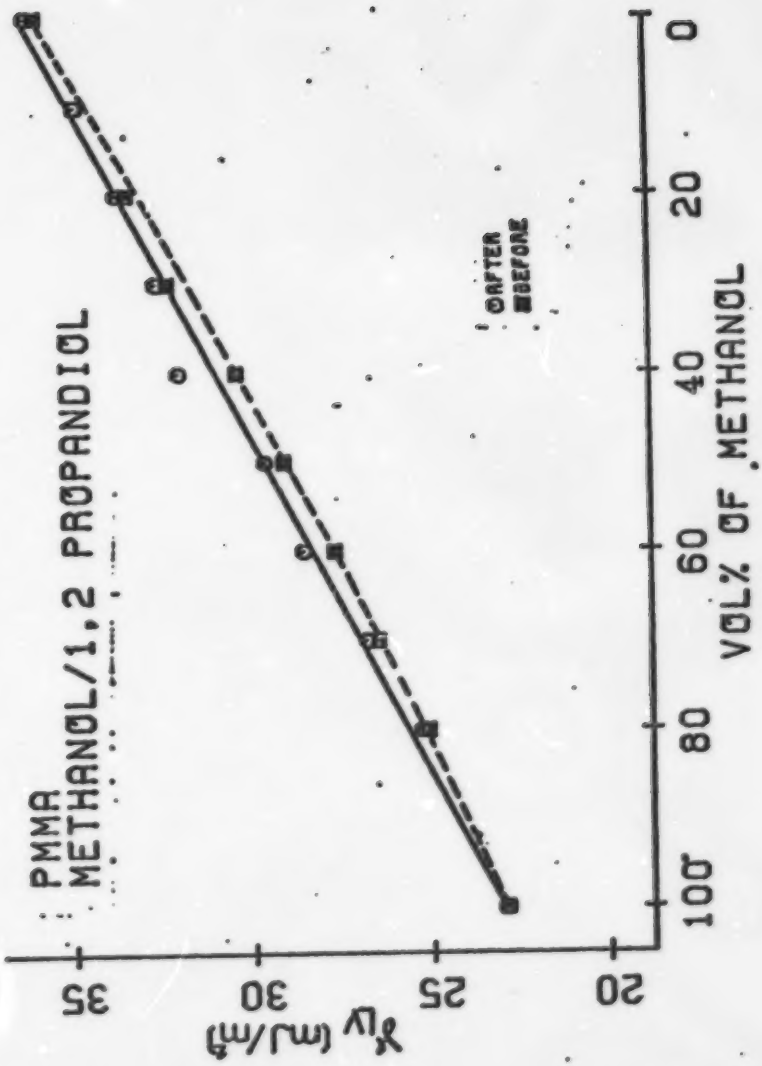

Figure 13. Surface Tension, γ_{LV}, of Liquid Medium (Methanol/1,2 Propandiol) versus Concentration of Methanol Before and After the Sedimentation Volume, V_{sed}, Measurement; ■: Before; o: After

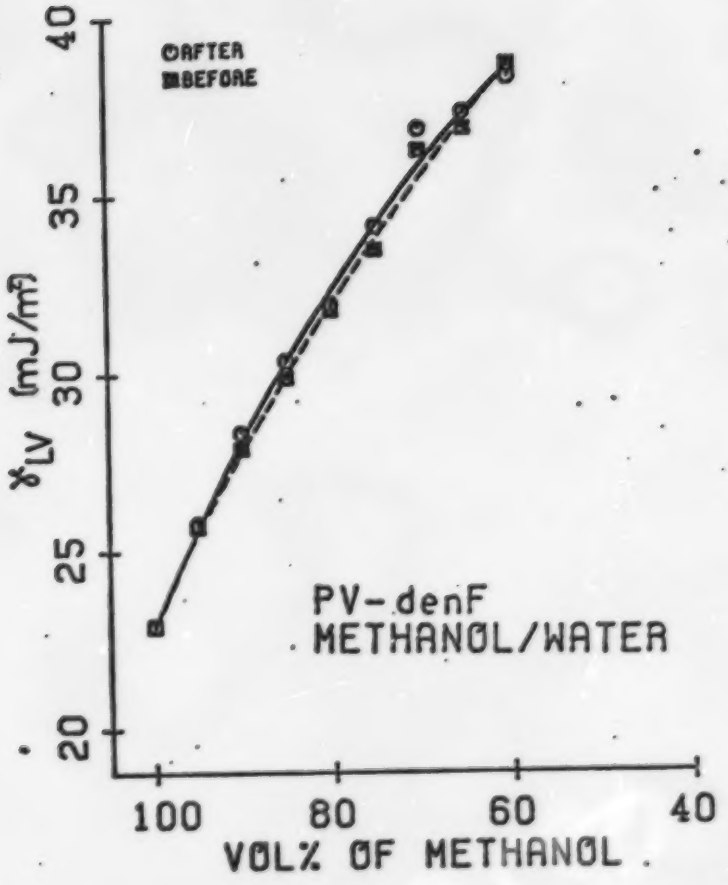

Figure 14. Surface Tension, γ_{LV}, of Liquid Medium (Methanol/Water) versus Concentration of Methanol Before and After the Sedimentation Volume, V_{sed}, Measurement; ■: Before; o: After

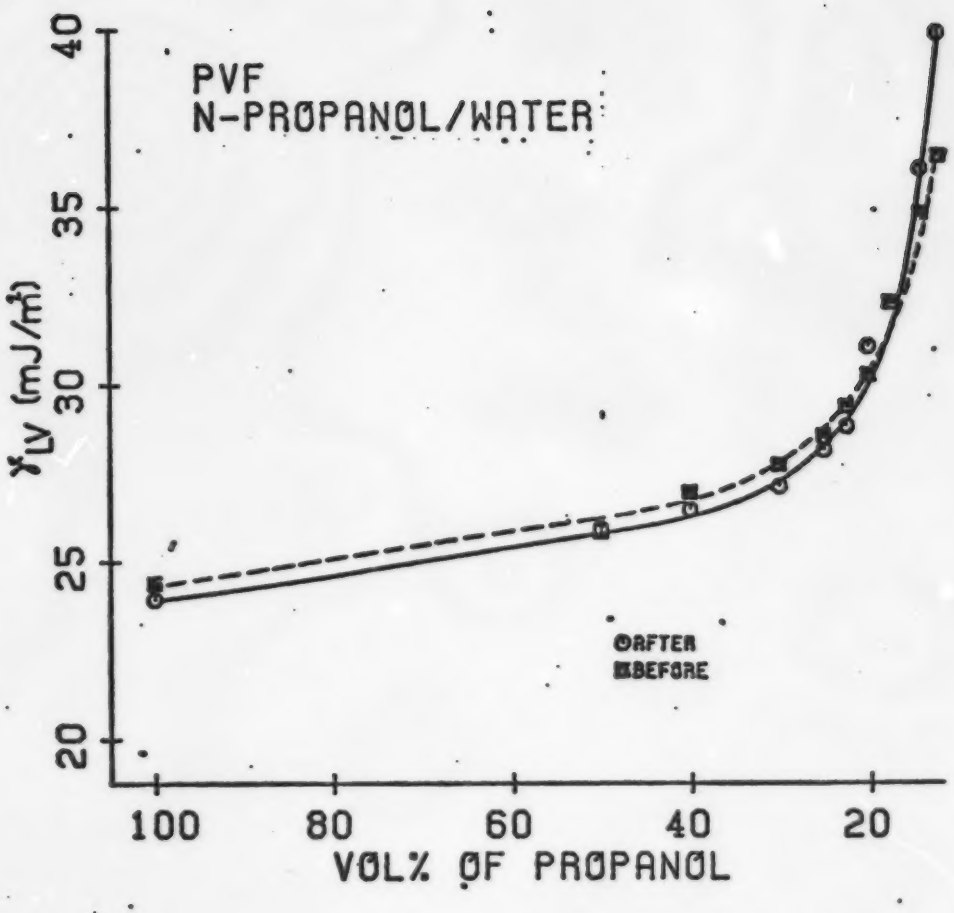

Figure 15. Surface Tension, γ_{LV}, of Liquid Medium (n-Propanol/Water) versus Concentration of n-Propanol Before and After the Sedimentation Volume, V_{sed}, Measurement; ■: Before; o: After

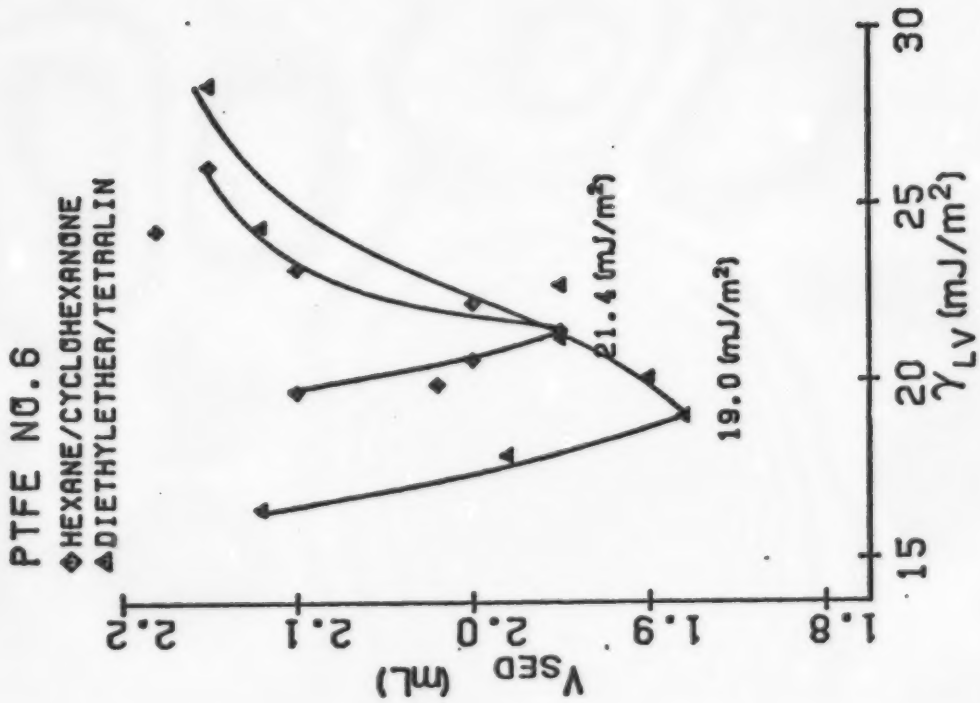

Figure 16. Sedimentation Volume, V_{sed}, as a Function of the Surface Tension, γ_{LV}, of Liquid Medium for PTFE No.6

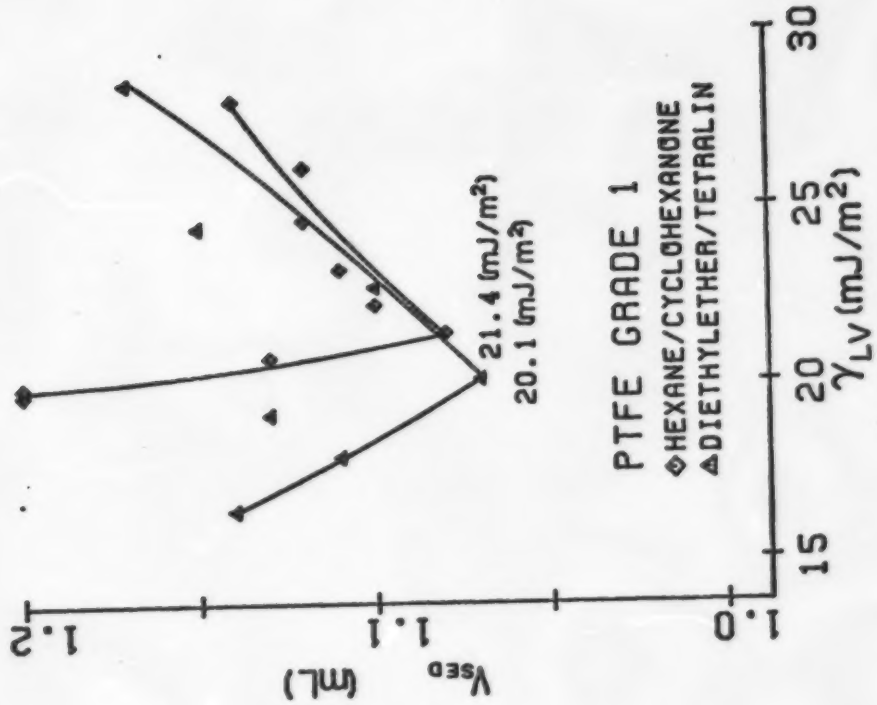

Figure 17. Sedimentation Volume, V_{sed}, as a Function of the Surface Tension, γ_{LV}, of Liquid Medium for PTFE Grade 1.

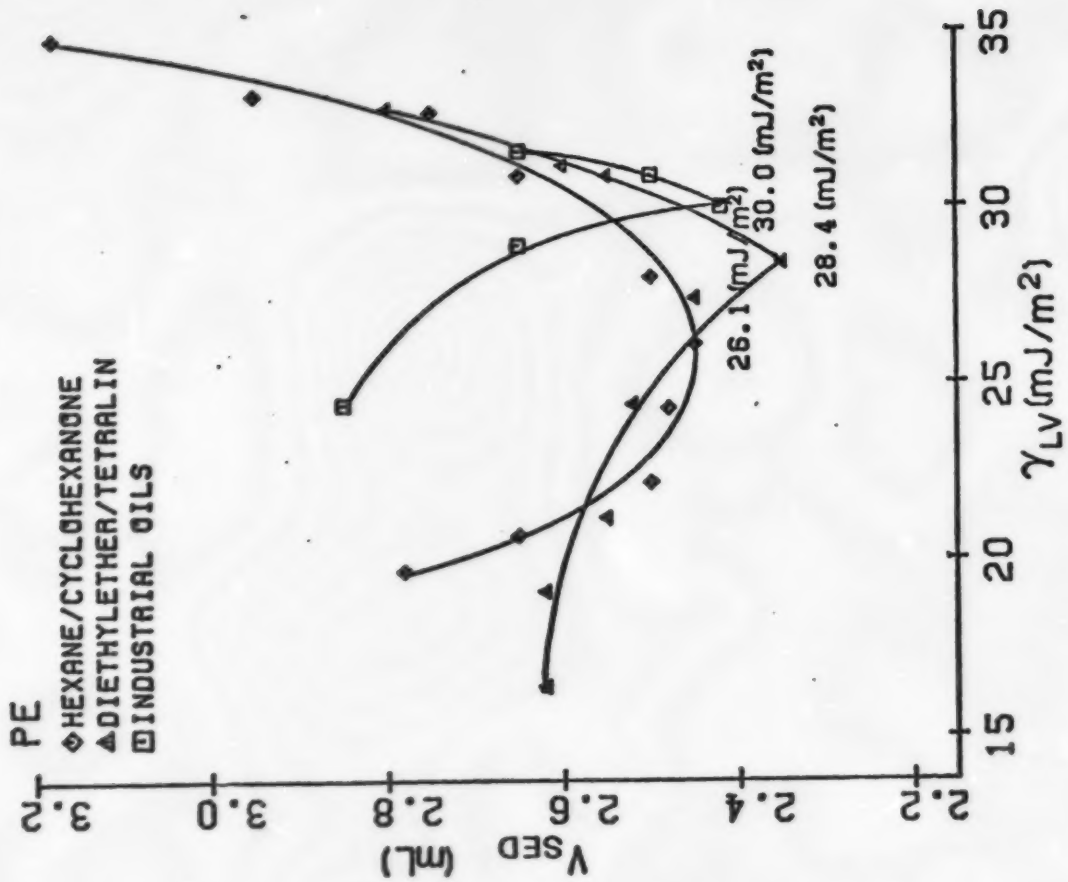

Figure 18. Sedimentation Volume, V_{sed}, as a Function of the Surface Tension, γ_{LV}, of Liquid Medium for PE

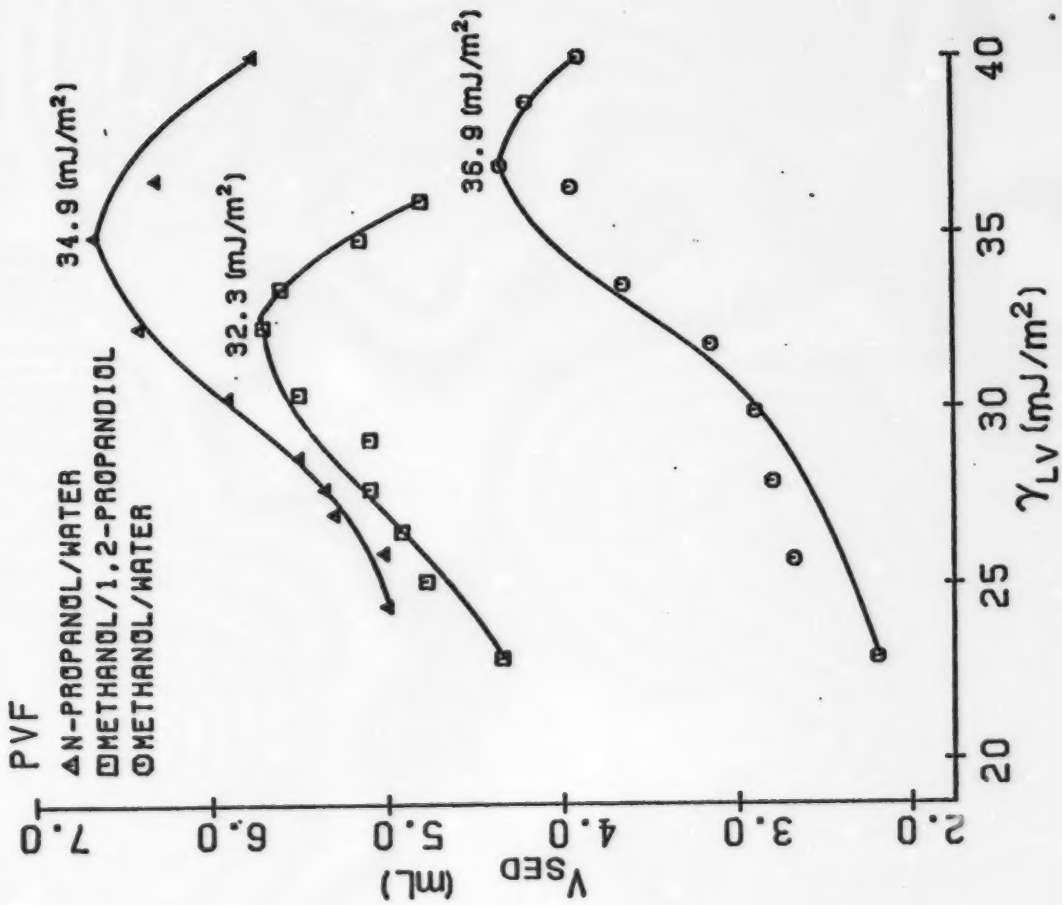

Figure 19. Sedimentation Volume, V_{sed}, as a Function of the Surface Tension, γ_{LV}, of Liquid Medium for PVF

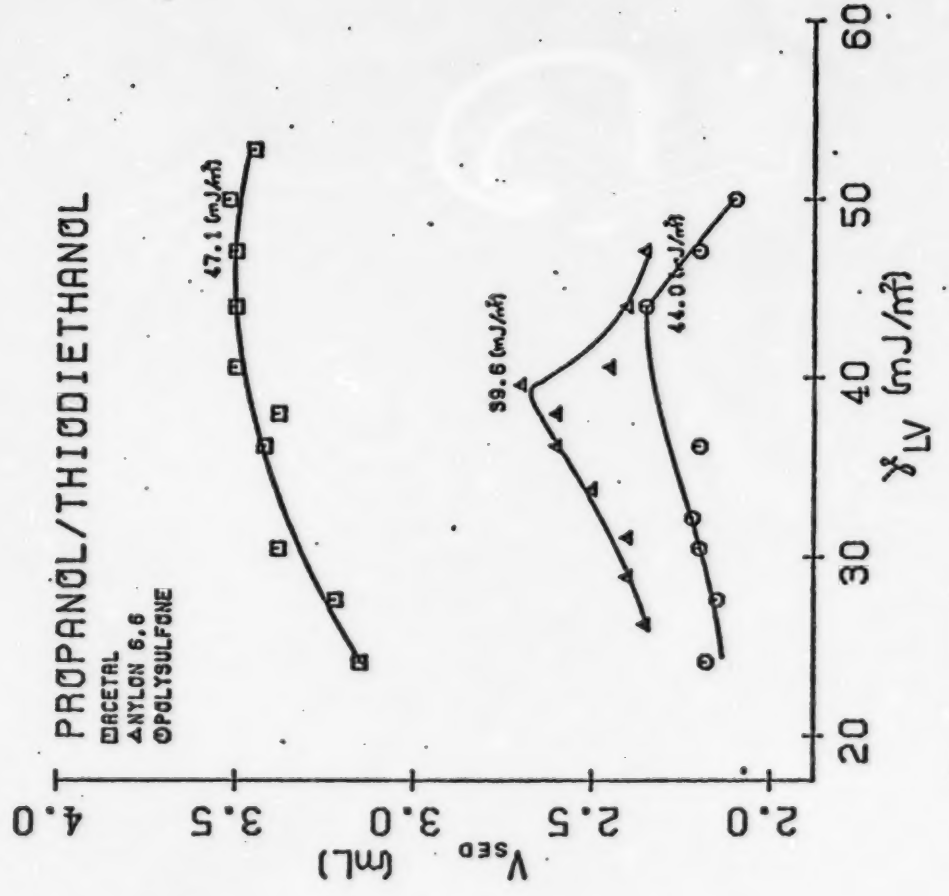

Figure 20. Sedimentation Volume, V_{sed}, as a Function of the Surface Tension, γ_{LV}, of Liquid Medium for Nylon 6,6, Acetal and Polysulfone

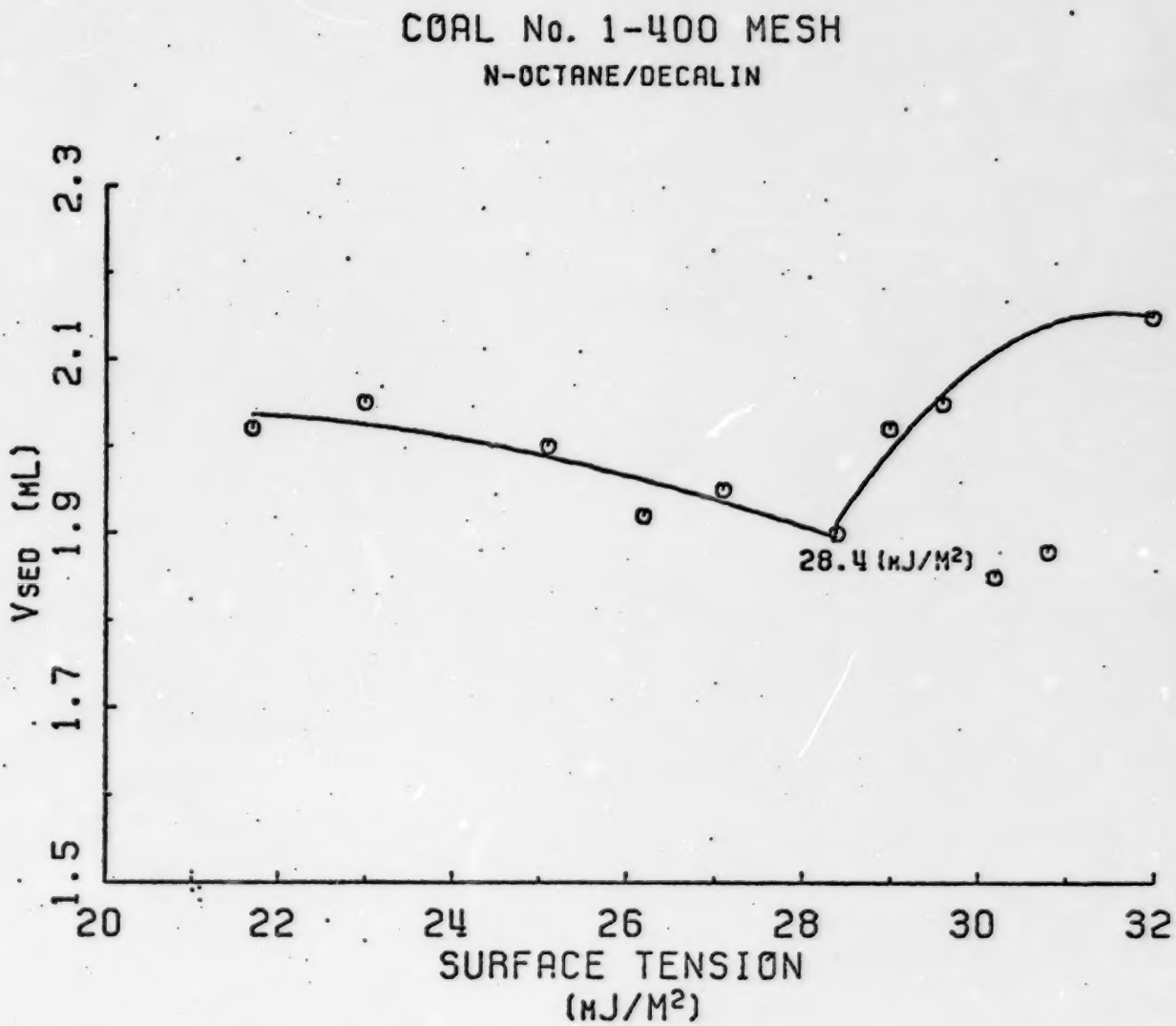

Figure 21. Sedimentation Volume, V_{sed}, for Coal No.1 in n-Octane/Decalin

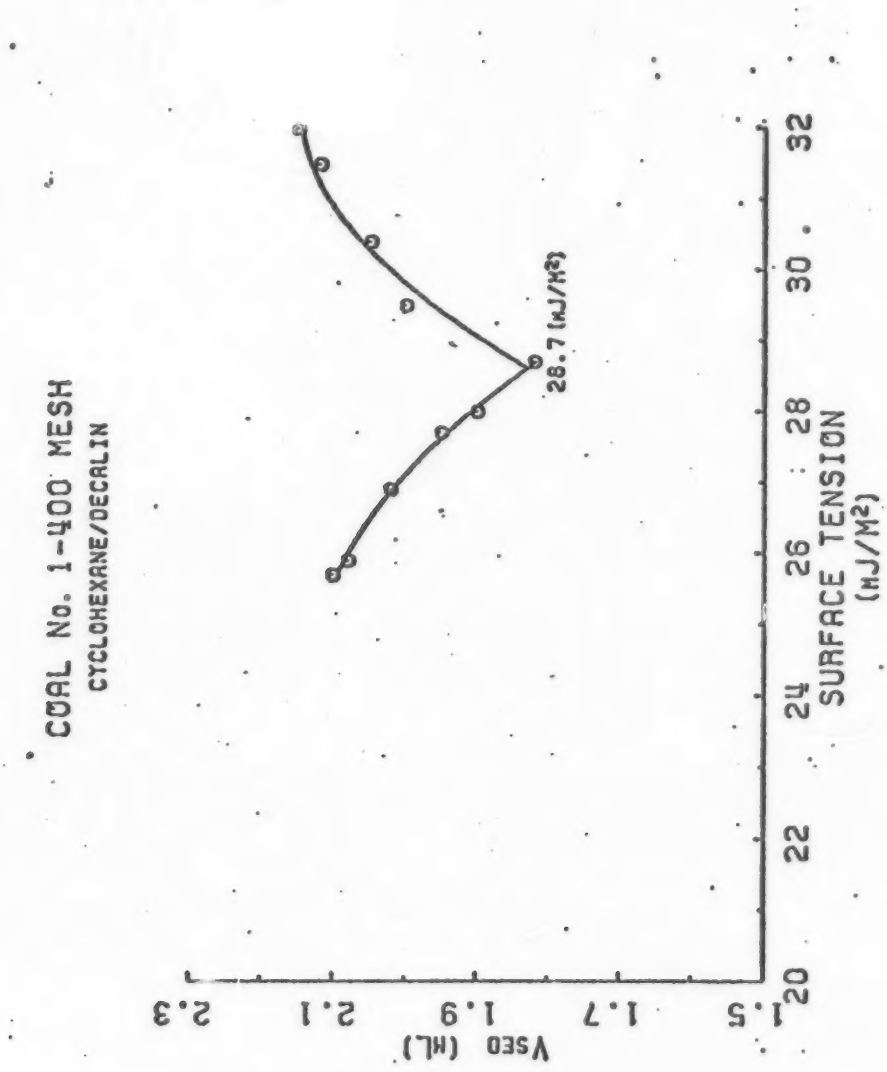

Figure 22. Sedimentation Volume, V_{sed}, for Coal No.1 in Cyclohexane/Decalin

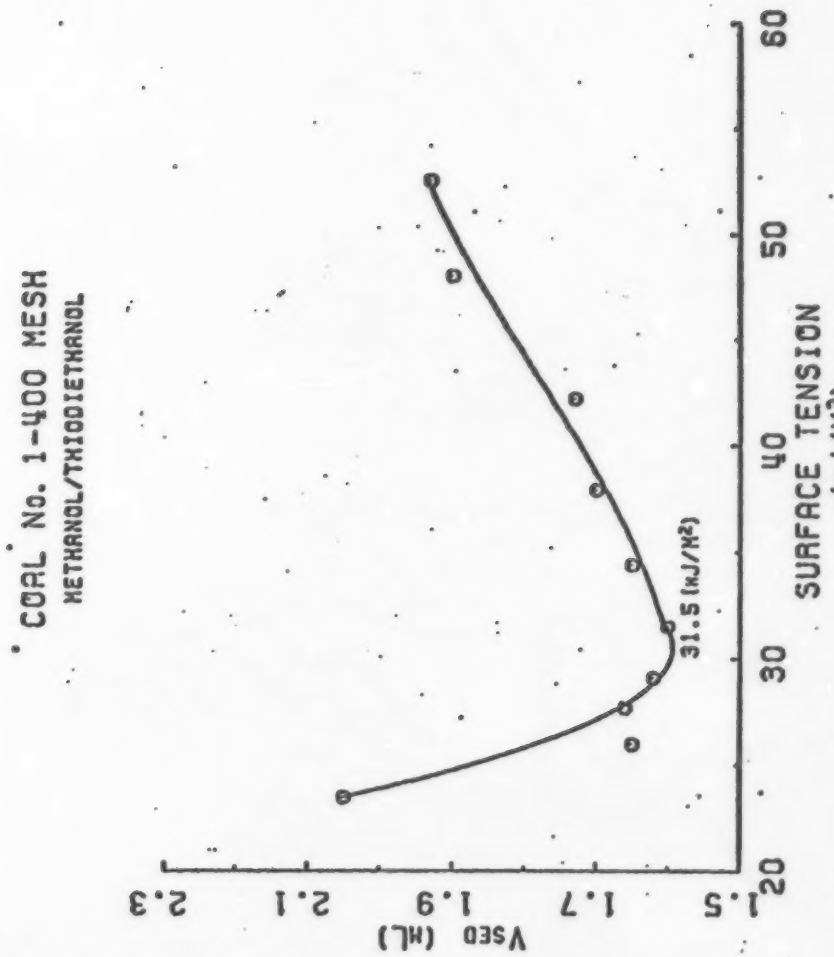

Figure 23. Sedimentation Volume, V_{sed}, for Coal No.1 in Methanol/Thiodiethanol

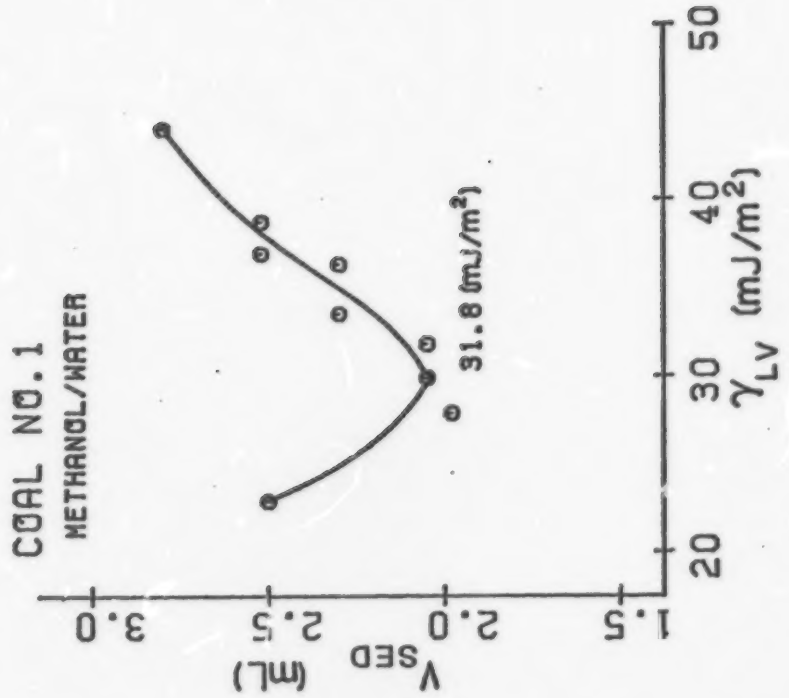

Figure 24. Sedimentation Volume, V_{sed}, for Coal No.1 in Methanol/Water

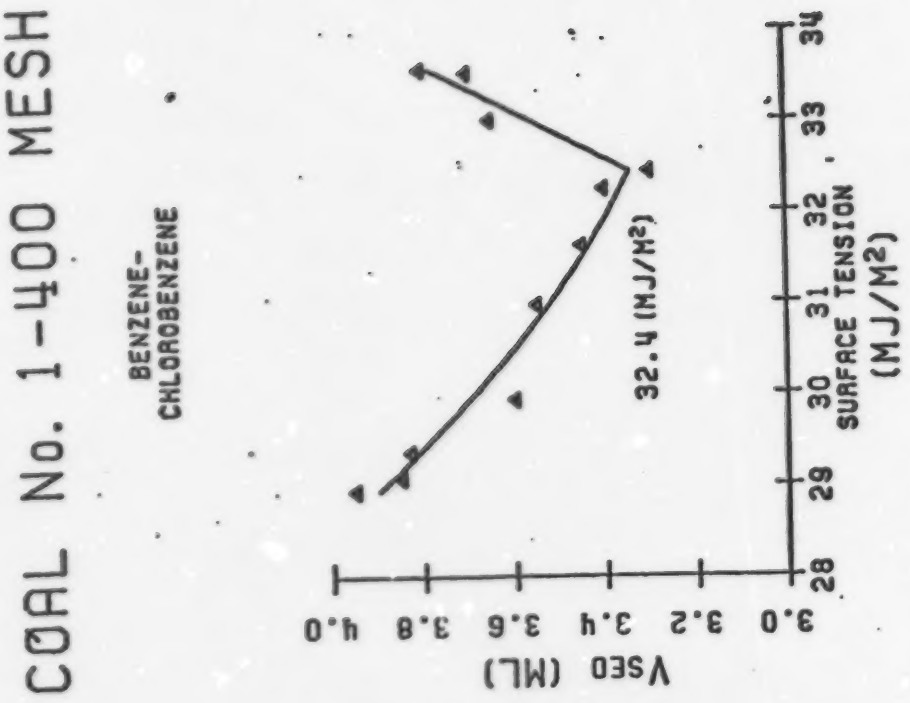

Figure 25. Sedimentation Volume, V_{sed}, for Coal No.1 in Benzene/Chlorobenzene

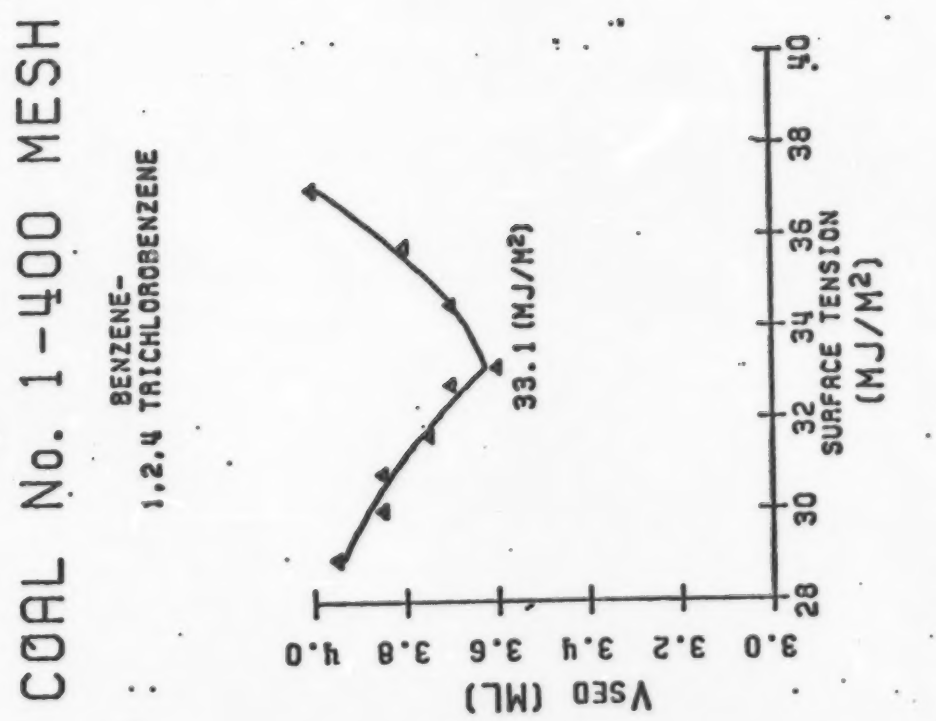

Figure 26. Sedimentation Volume, V_{sed}, for Coal No.1 in Benzene/1,2,4 Trichlorobenzene

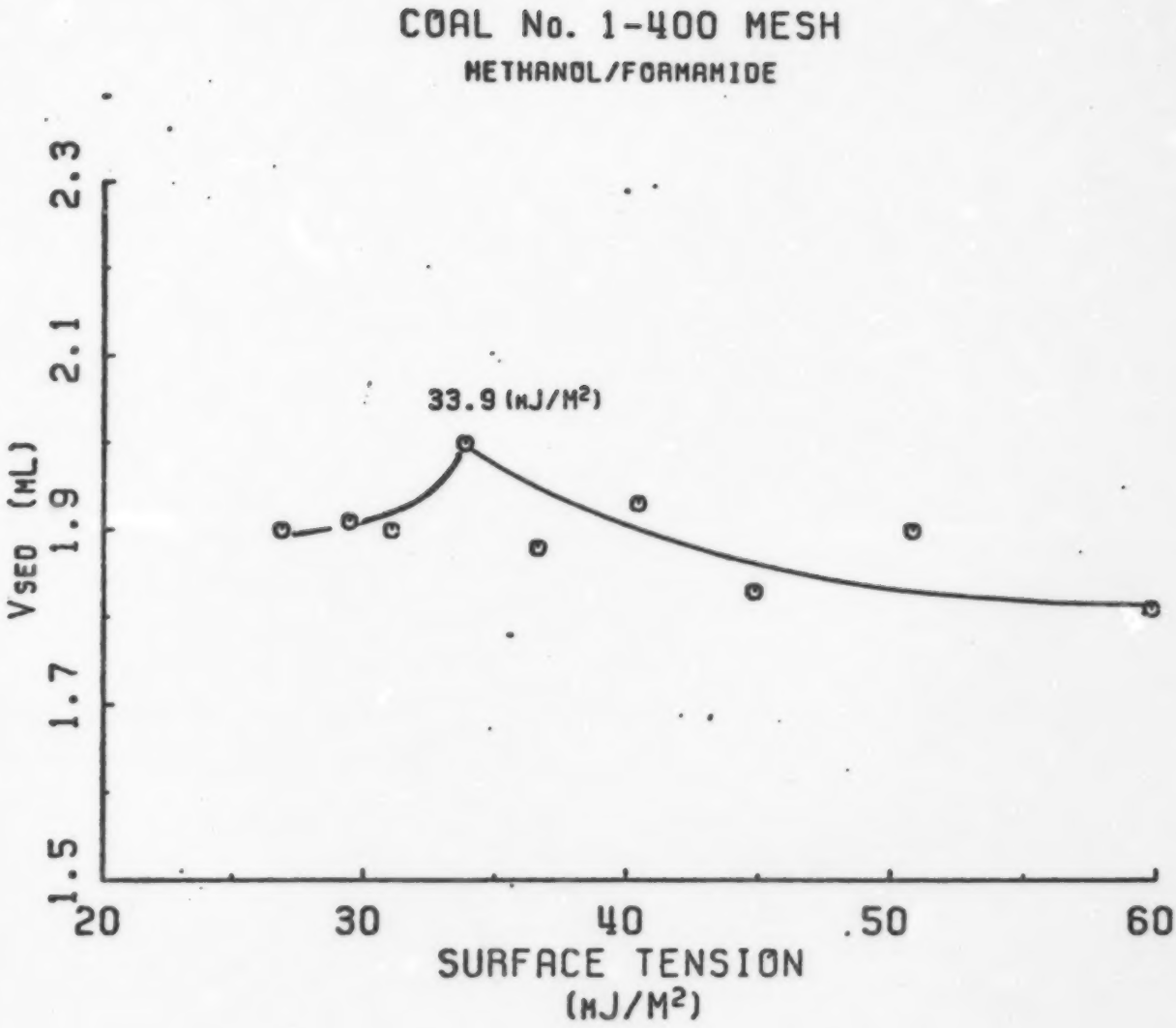

Figure 27. Sedimentation Volume, V_{sed}, for Coal No.1 in Methanol/Formamide

COAL No. 1-400 MESH

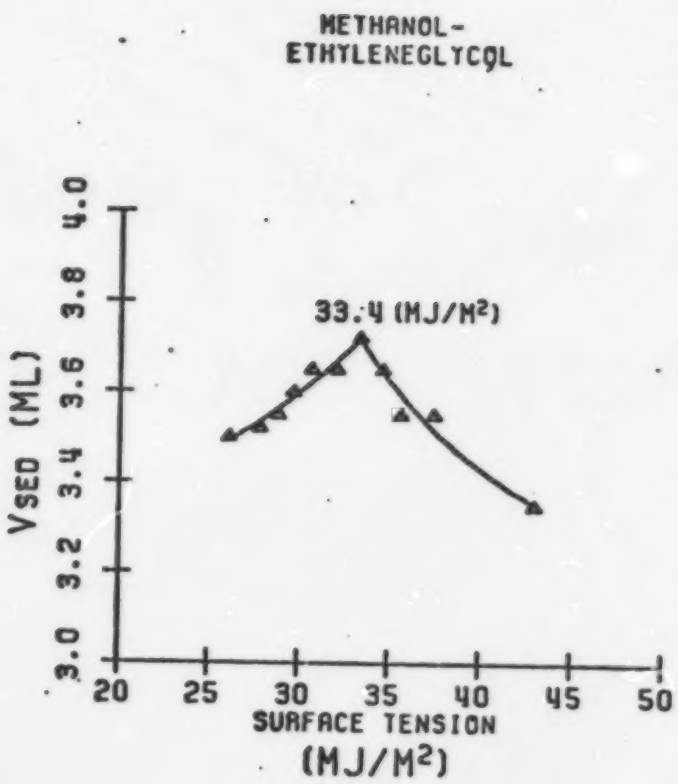

Figure 28. Sedimentation Volume, V_{sed}, for Coal No.1 in Methanol/Ethyleneglycol

COAL No. 1-400 MESH

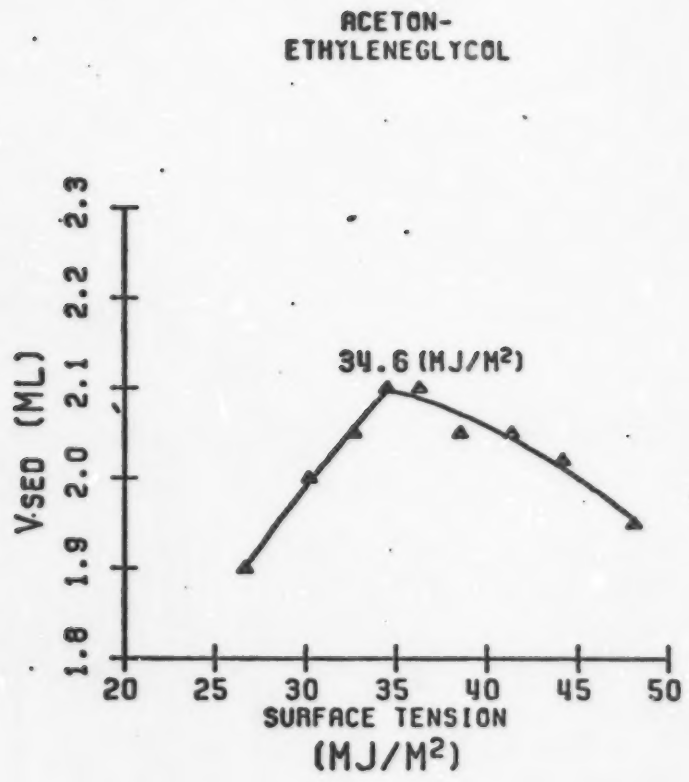

Figure 29. Sedimentation Volume, V_{sed}, for Coal No.1 in Acetone/Ethyleneglycol

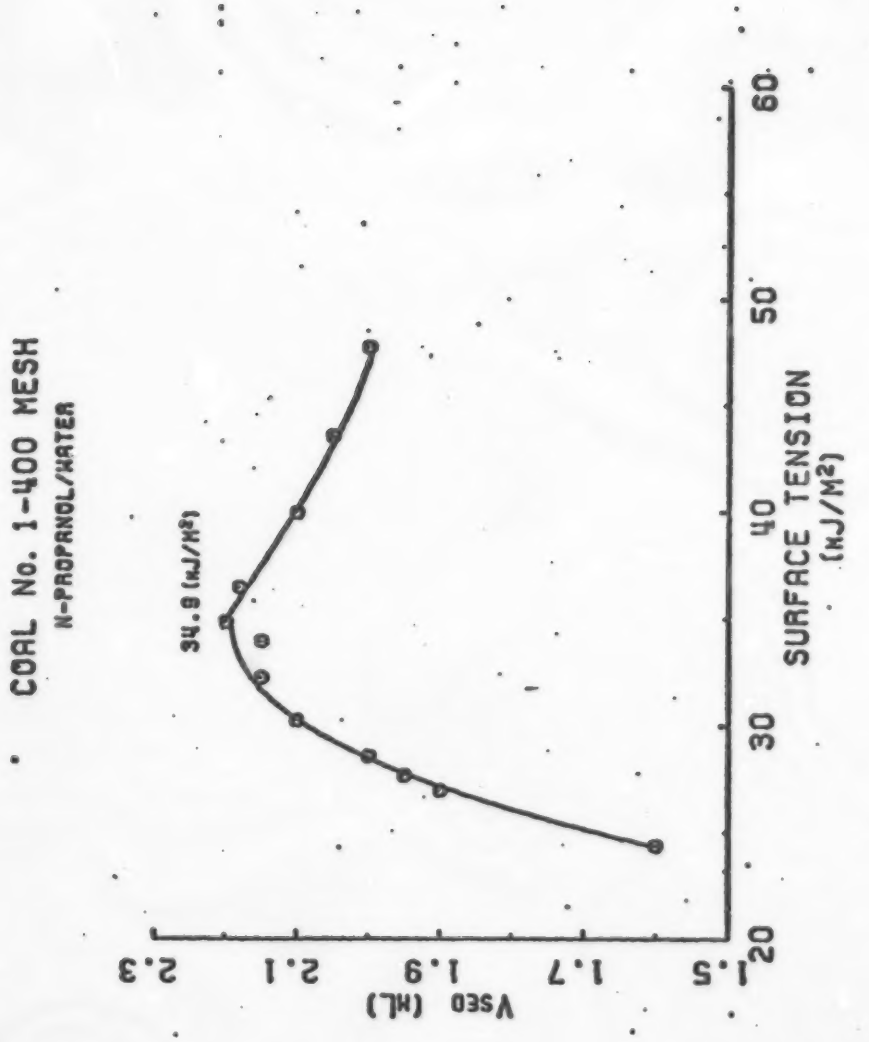

Figure 30. Sedimentation Volume, V_{sed}, for Coal No.1 in n-Propanol/Water

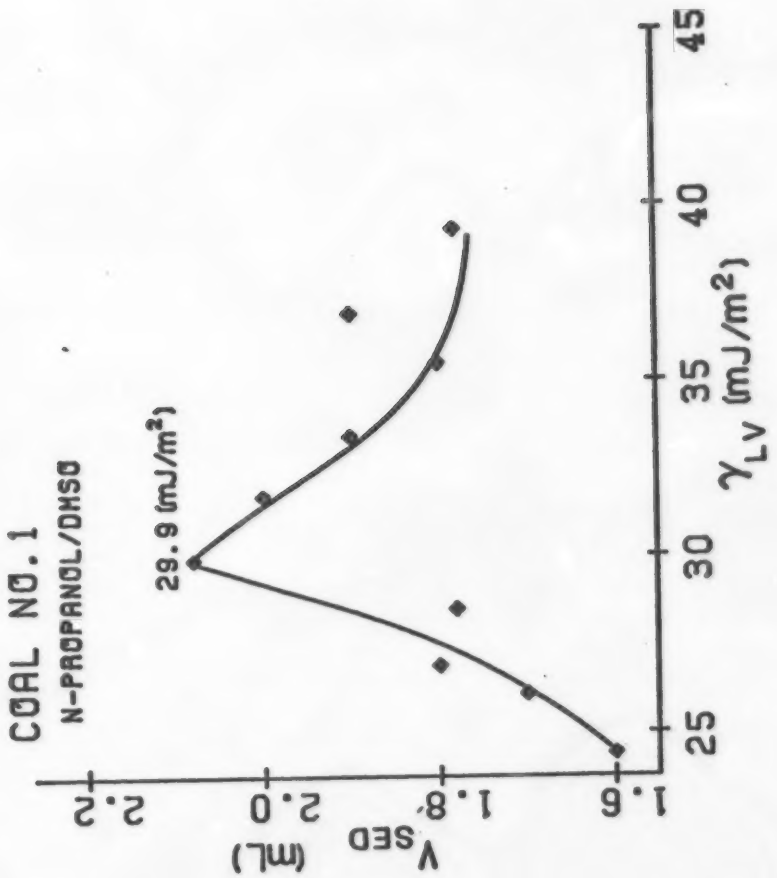

Figure 31. Sedimentation Volume, V_{sed}, for Coal No.1 in n-Propanol/DMSO

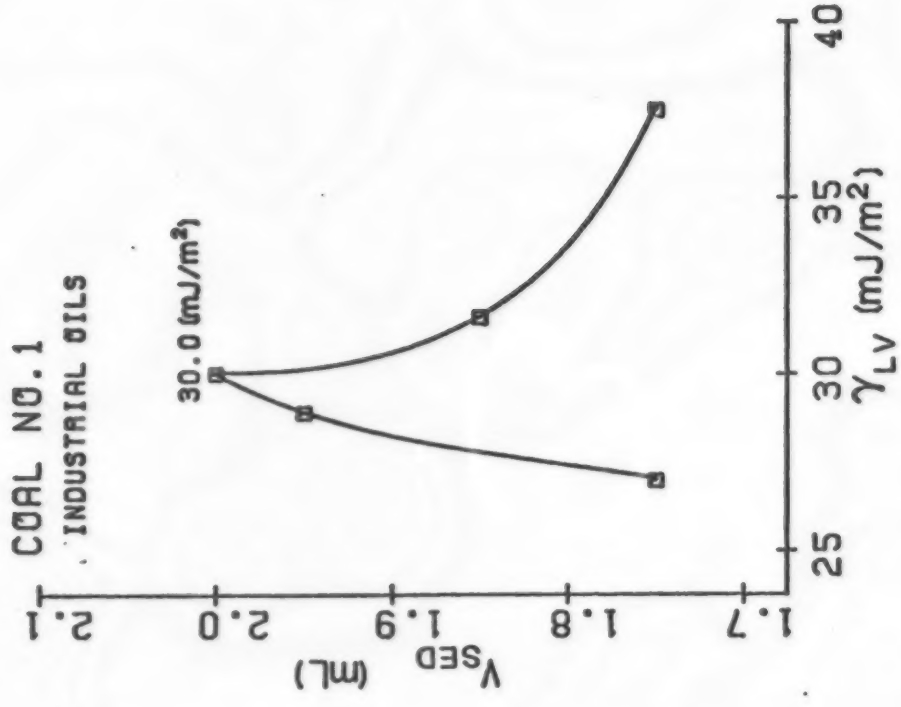

Figure 32. Sedimentation Volume, V_{sed}, for Coal No.1 in Industrial Oils

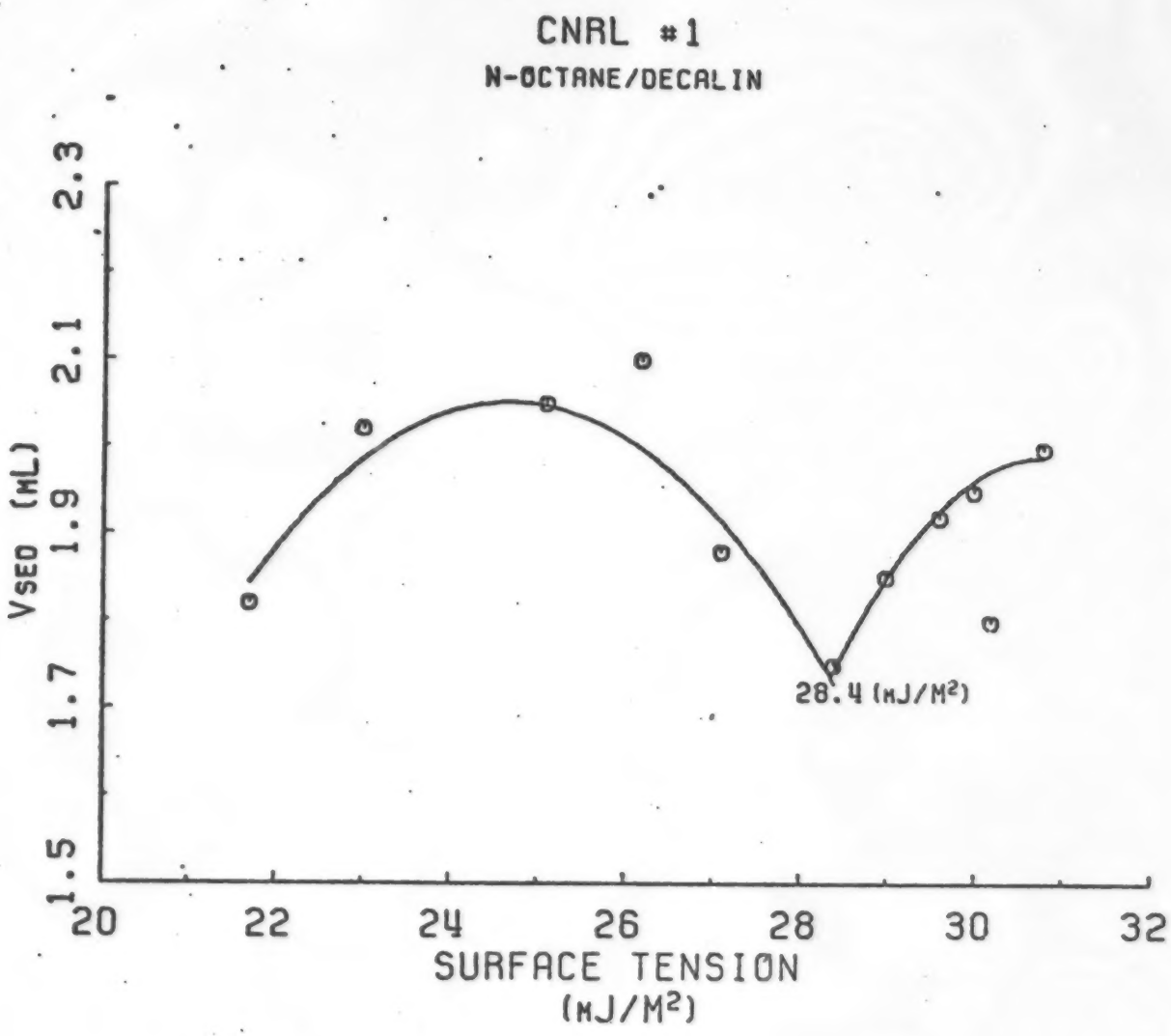

Figure 33. Sedimentation Volume, V_{sed}, for CNRL #1 Coal in n-Octane/Decalin

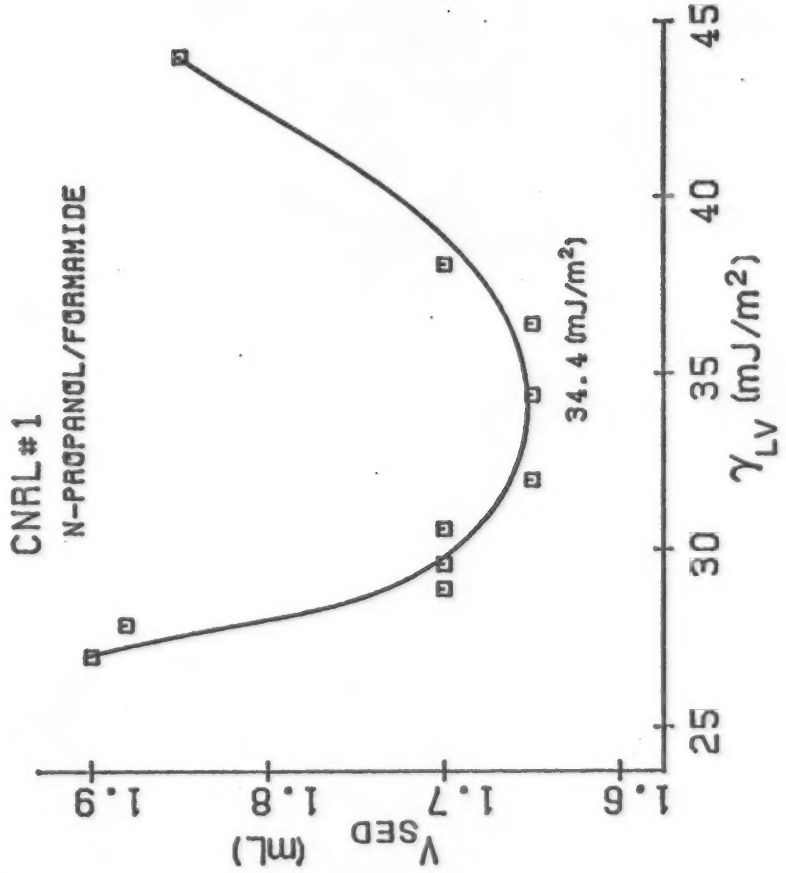

Figure 34. Sedimentation Volume, V_{sed}, for CNRL #1 Coal in n-Propanol/Formamide

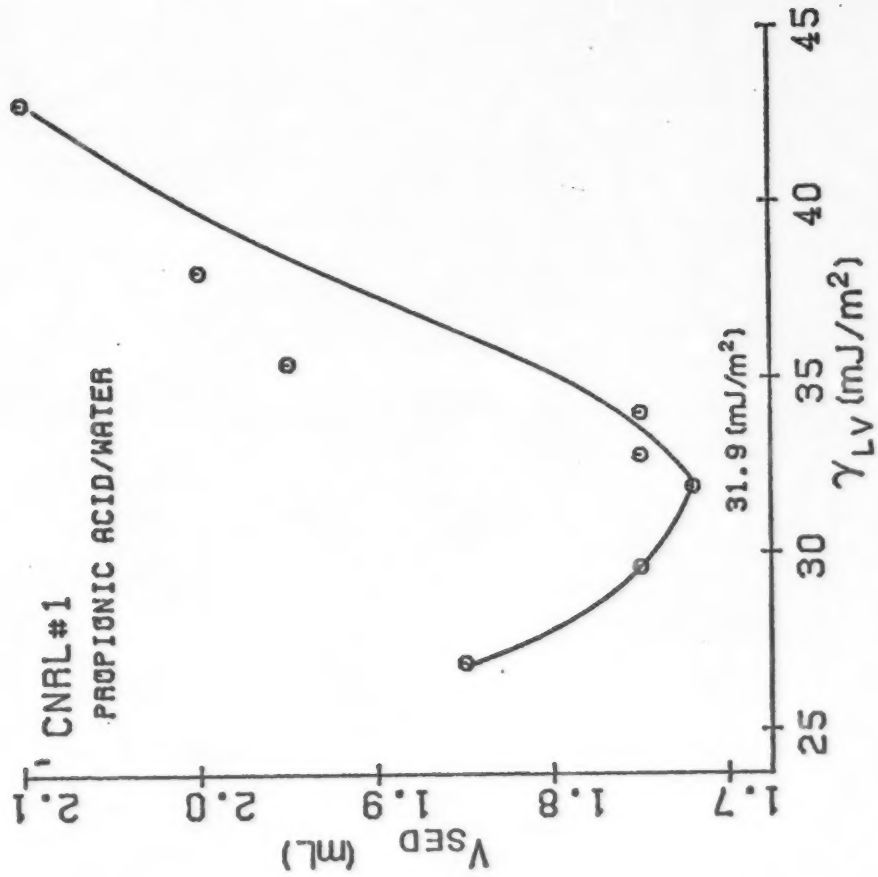

Figure 35. Sedimentation Volume, V_{sed}, for CNRL #1 Coal in Propionic Acid/water

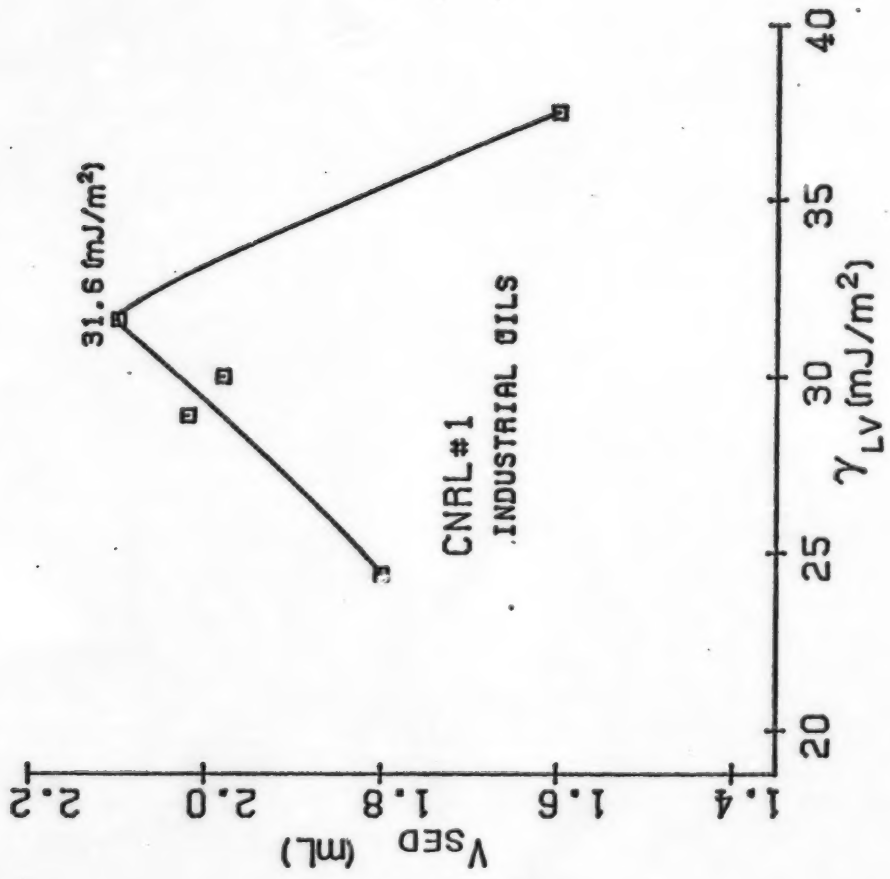

Figure 36. Sedimentation Volume, V_{sed}, for CNRL #1 Coal in Industrial Oils

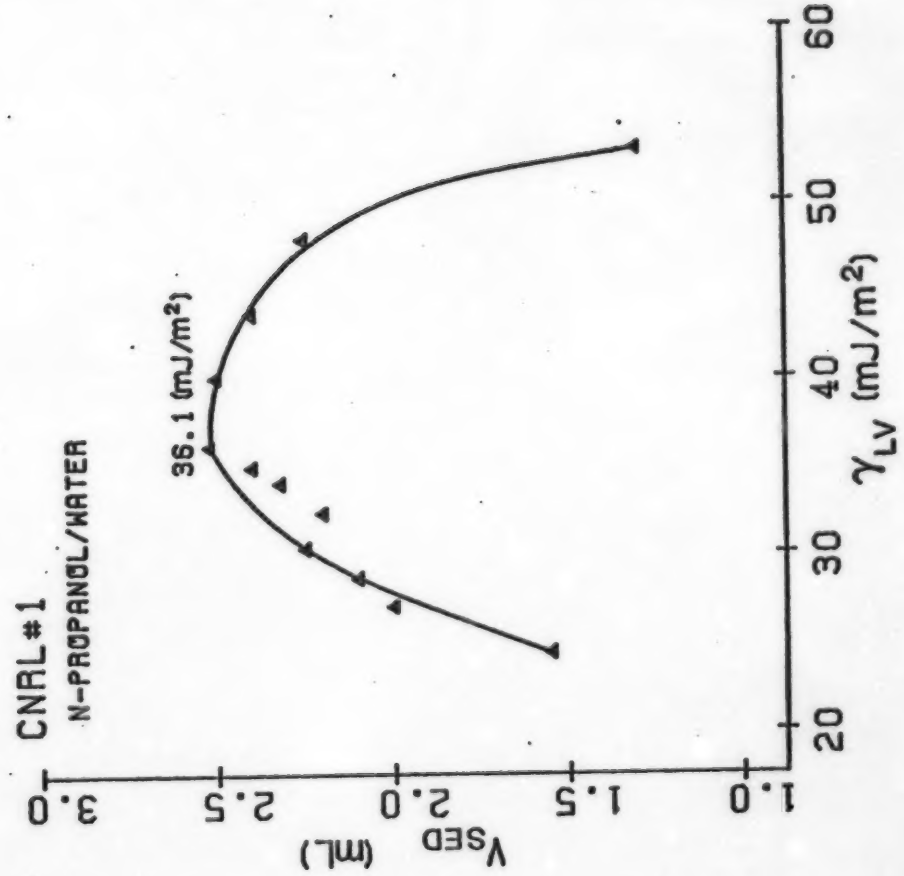

Figure 37. Sedimentation Volume, V_{sed}, for CNRL #1 Coal in n-Propanol/Water

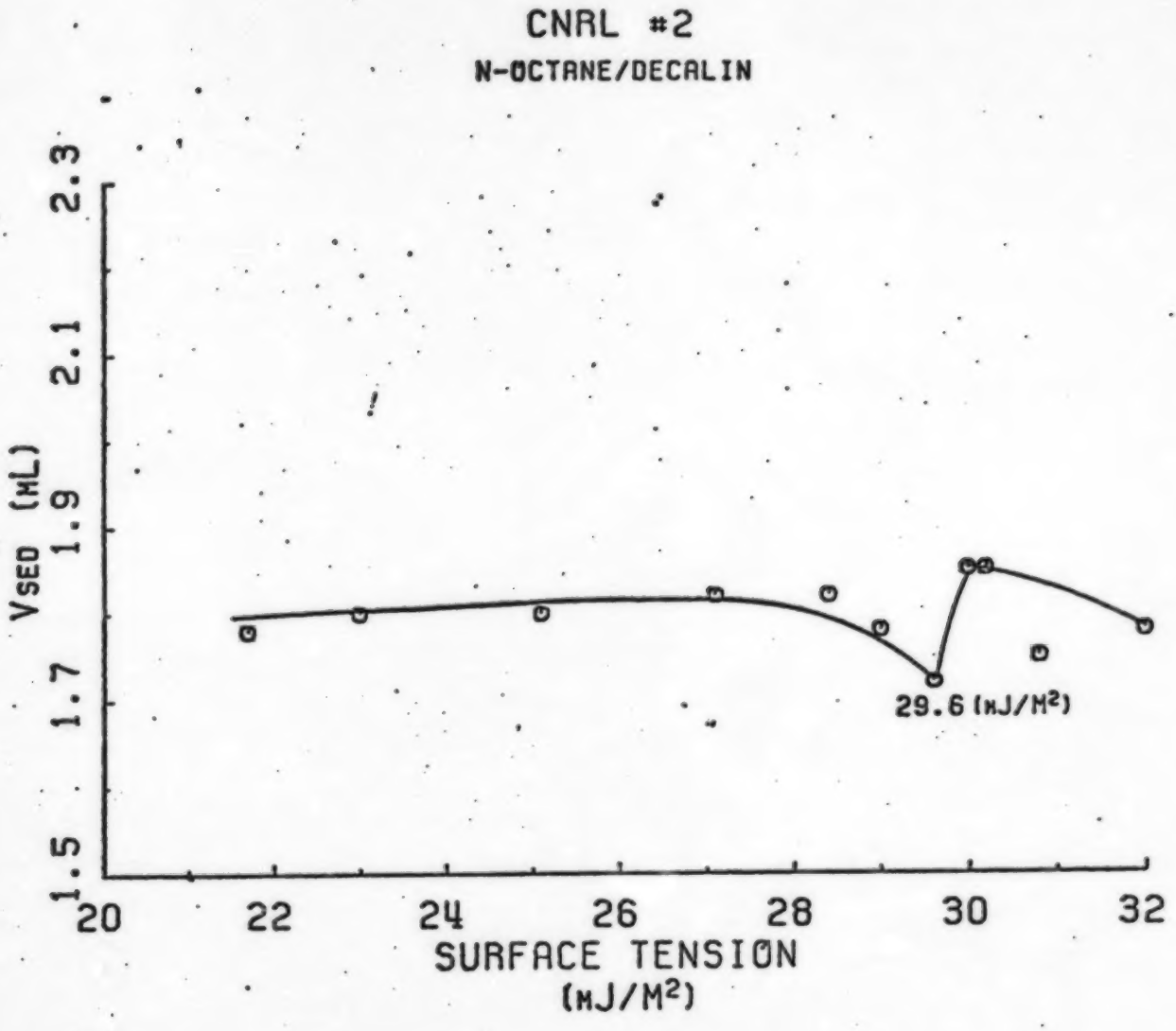

Figure 38. Sedimentation Volume, V_{sed}, for CNRL #2 Coal in n-Octane/Decalin

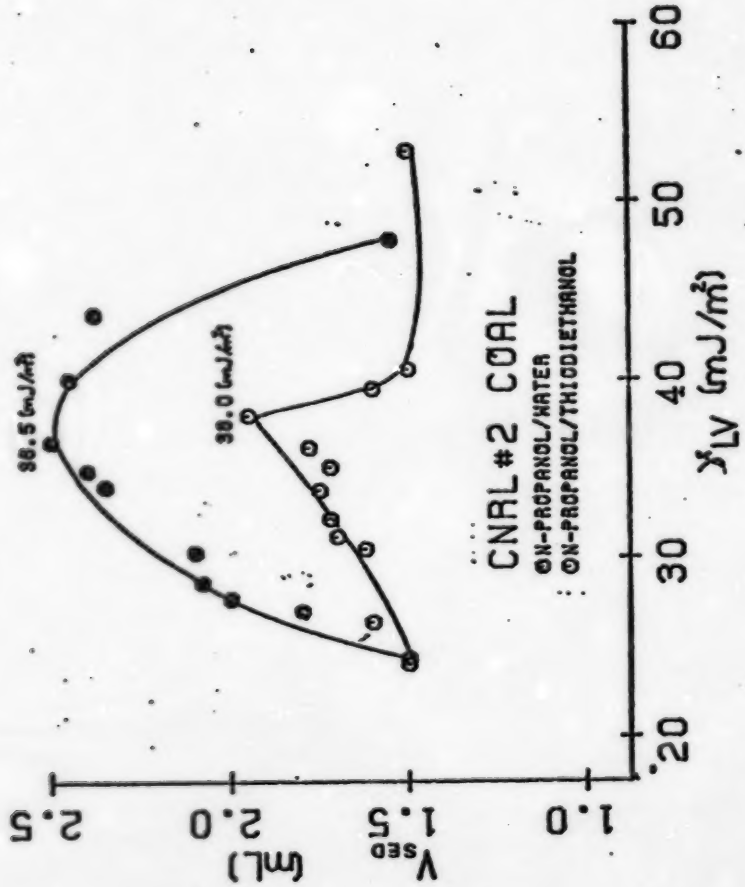

Figure 39. Sedimentation Volume, V_{sed}, for CNRL #2 Coal in n-Propanol/Water and n-Propanol/Thiodiethanol

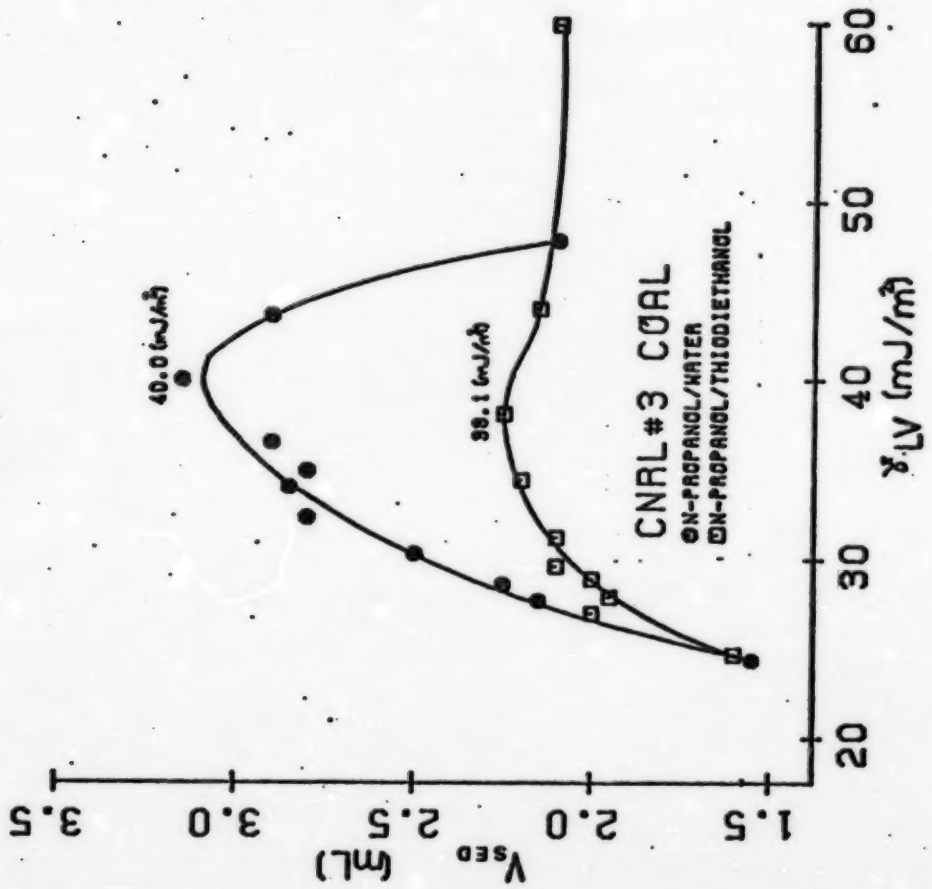

Figure 40. Sedimentation Volume, V_{sed}, for CNRL #3 Coal in n-Propanol/Water and n-Propanol/Thiodiethanol

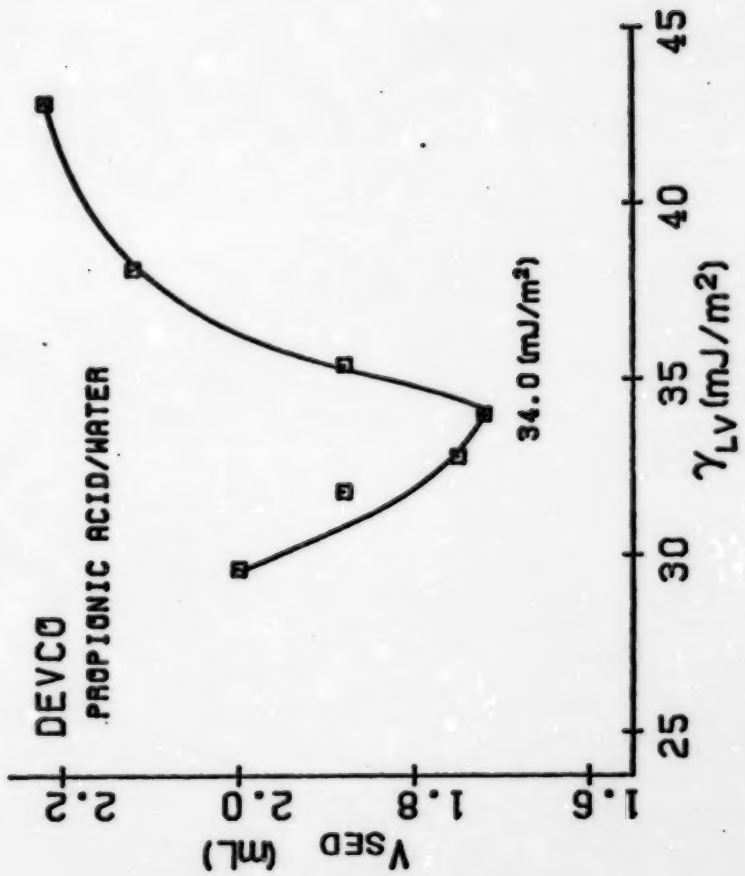

Figure 41. Sedimentation Volume, V_{sed}, for DEVCO Coal in Propionic Acid/Water

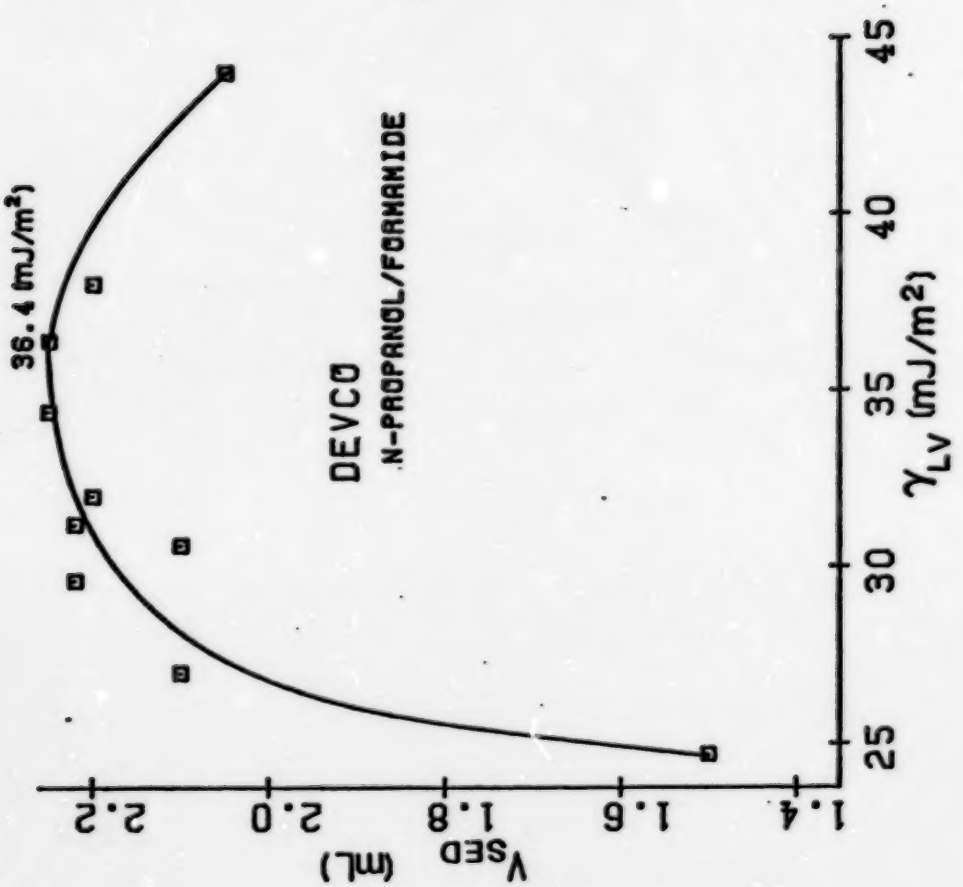

Figure 42. Sedimentation Volume, V_{sed}, for DEVCO Coal in n-Propanol/Formamide

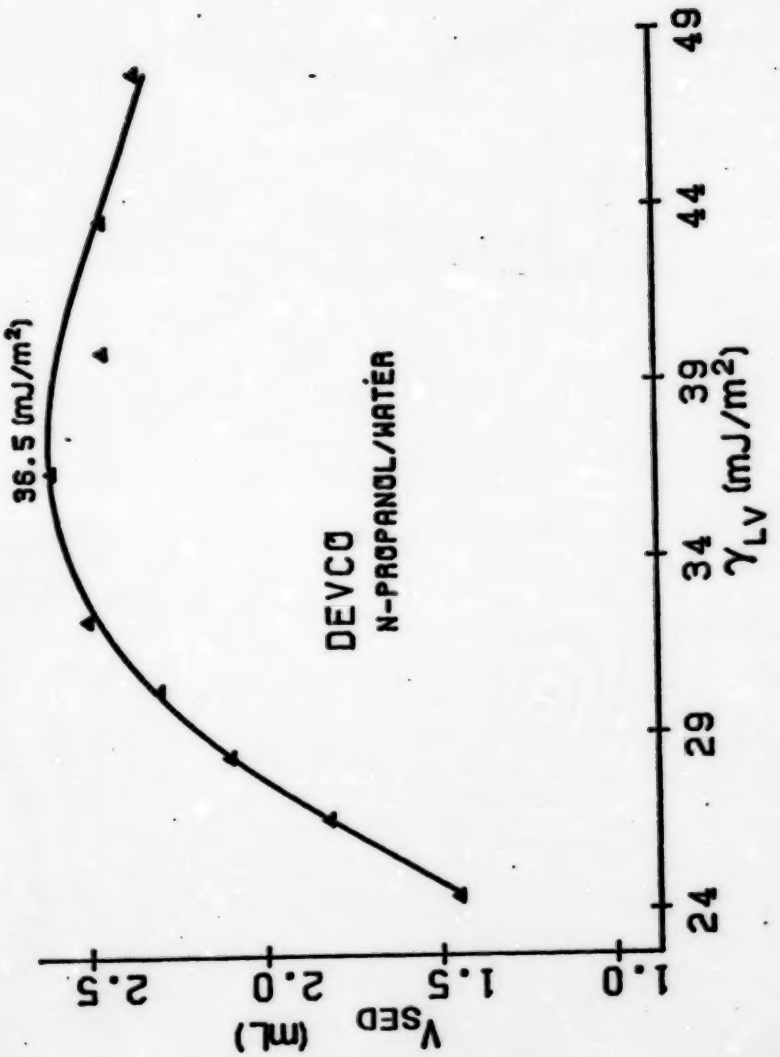

Figure 43. Sedimentation Volume, V_{sed}, for DEVCO Coal in n-Propanol/Water

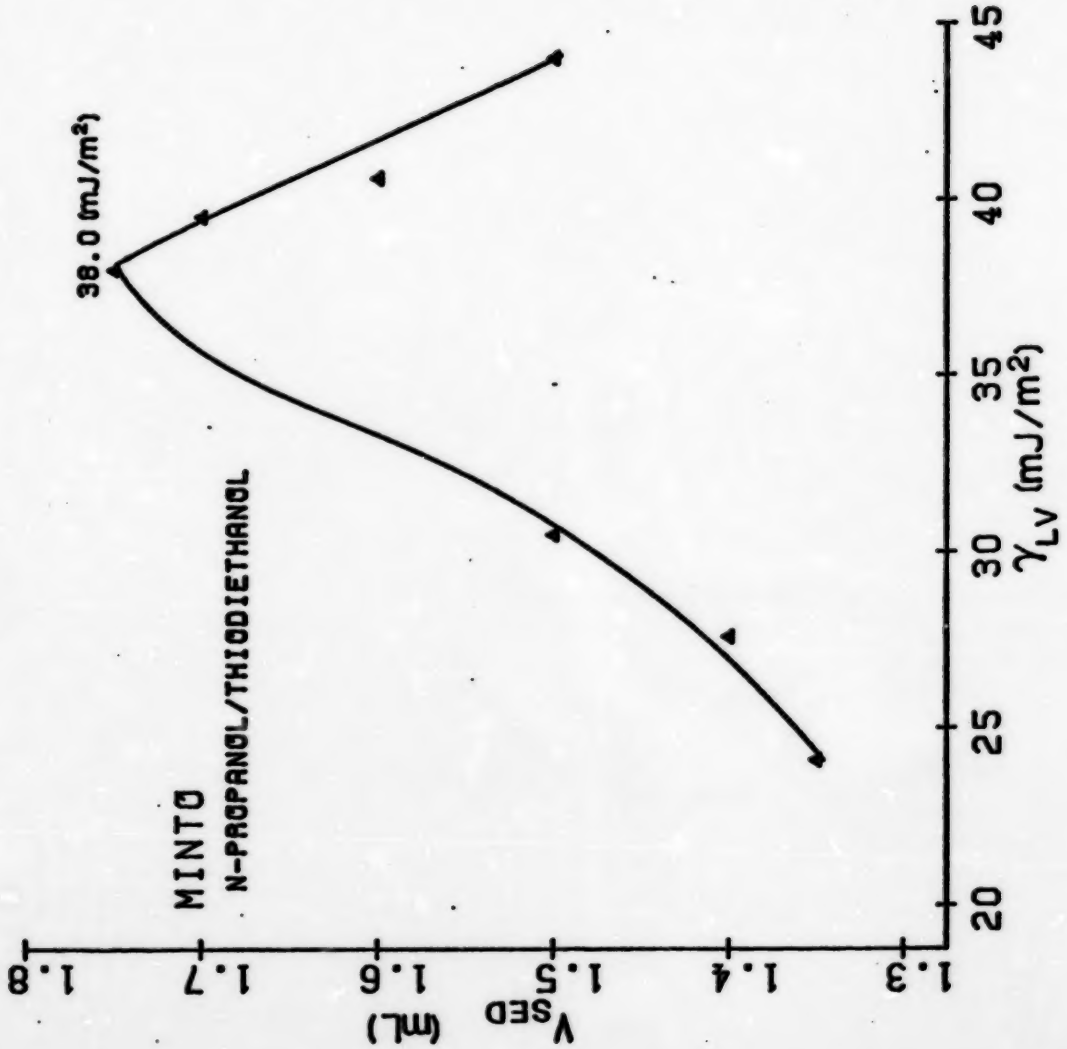

Figure 44. Sedimentation Volume, V_{sed}, for MINTO R.O.M. Coal in n-Propanol/Thiodiethanol

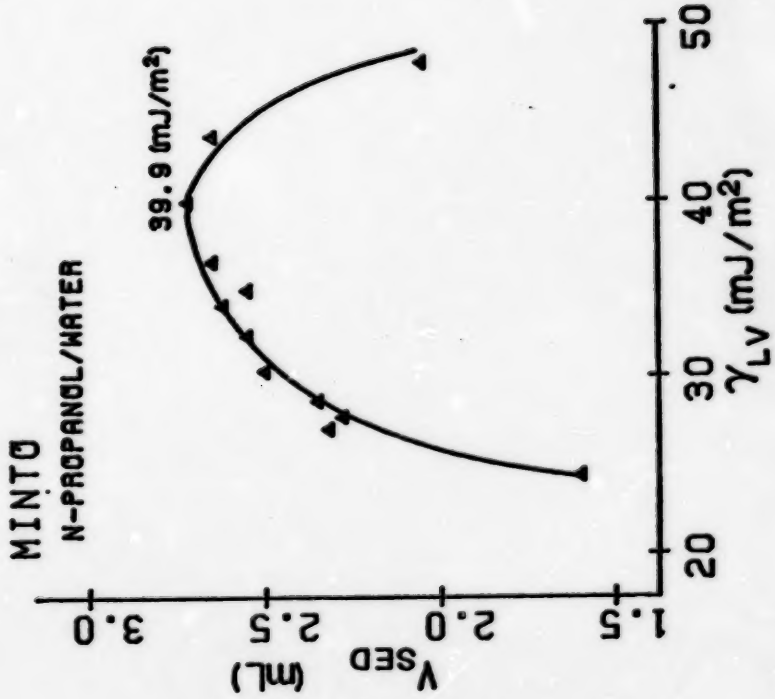

Figure 45. Sedimentation Volume, V_{sed}, for MINTO R.O.M. Coal in n-Propanol/Water

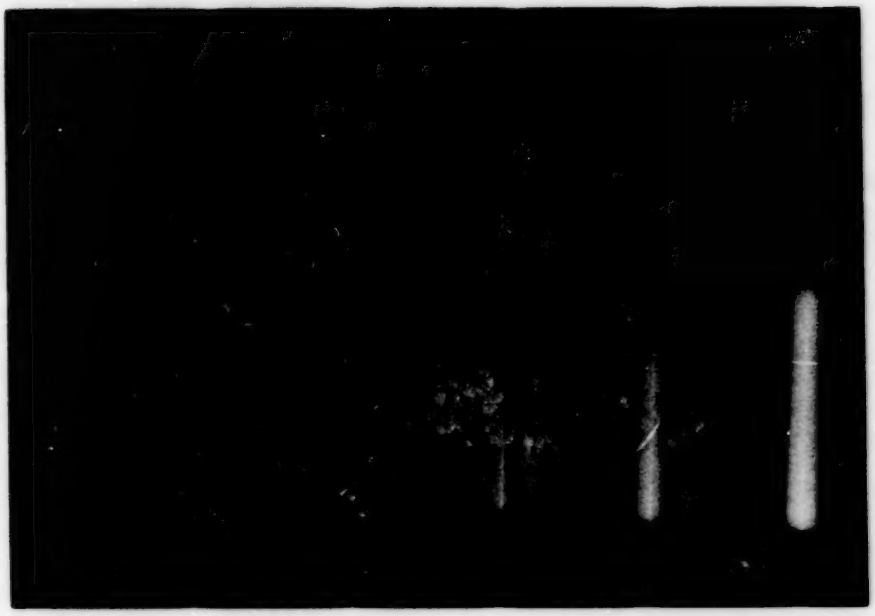

Figure 46. Sedimentation Volume, V_{sed}, for PTFE in n-Hexane/Cyclohexanone

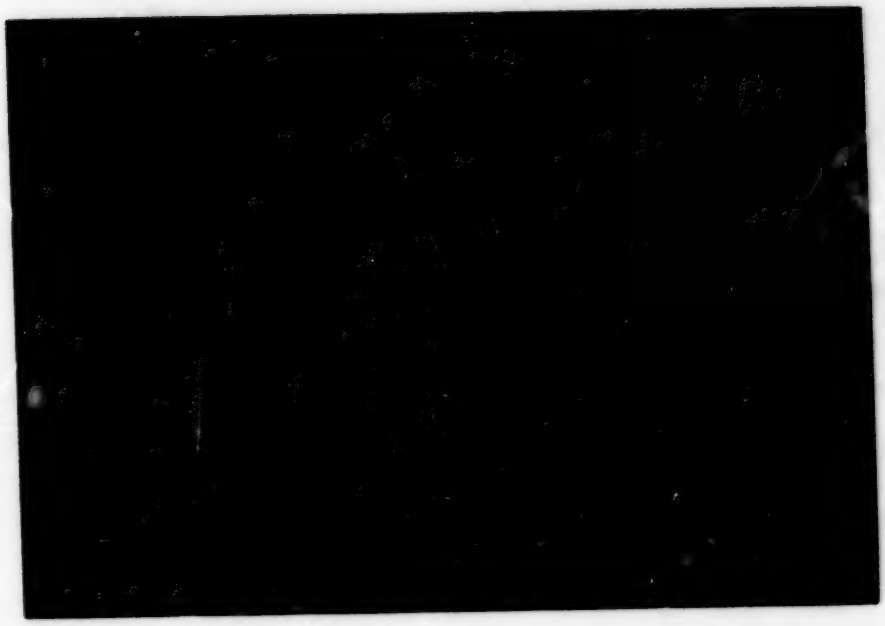

Figure 47. Sedimentation Volume, V_{sed}, for Nylon 6,6 in n-Propanol/Thiodiethanol

Figure 48. Sedimentation Volume, V_{sed}, for Coal No.1 in n-Propanol/Water

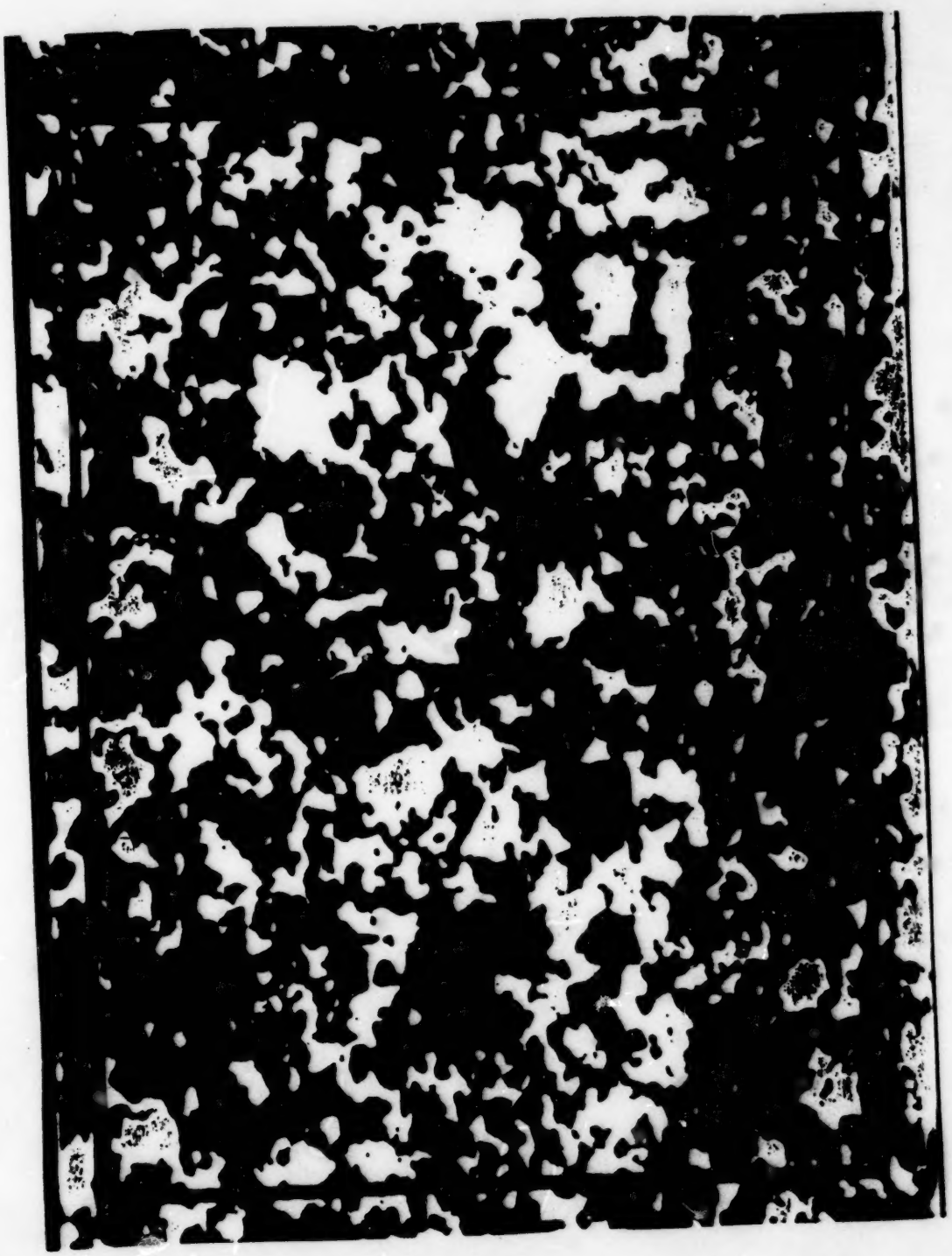

Figure 49. Image of Coal Particles Adhered on LDPE (in 3% DMSO)

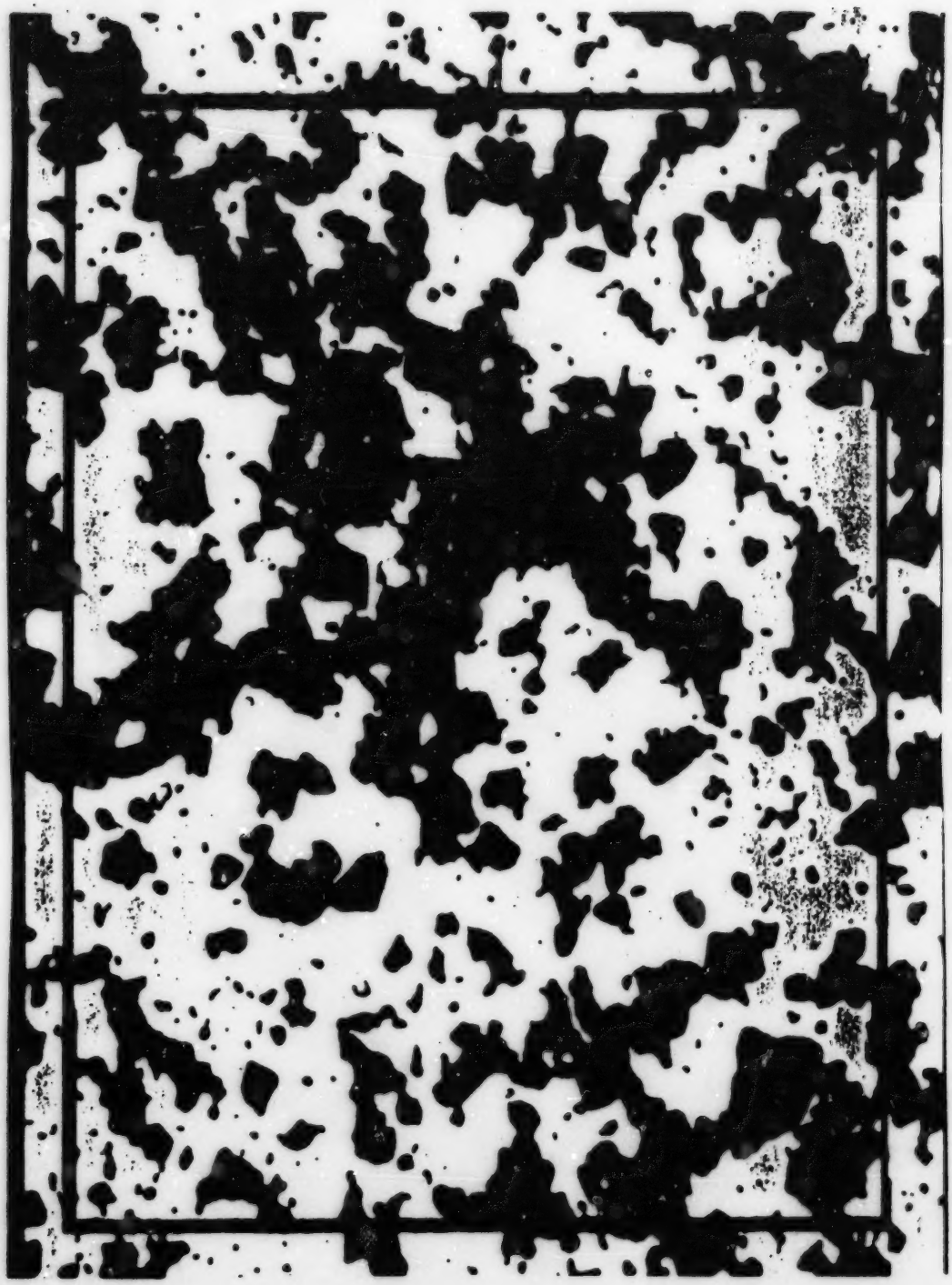

Figure 50. Image of Coal Particles Adhered on SPS (in 3% DMSO)

Figure 51. Image of Coal Particles
Adhered on LDPE (in 15% DMSO)

Figure 52. Image of Coal Particles Adhered on SPS (in 15% DMSO)

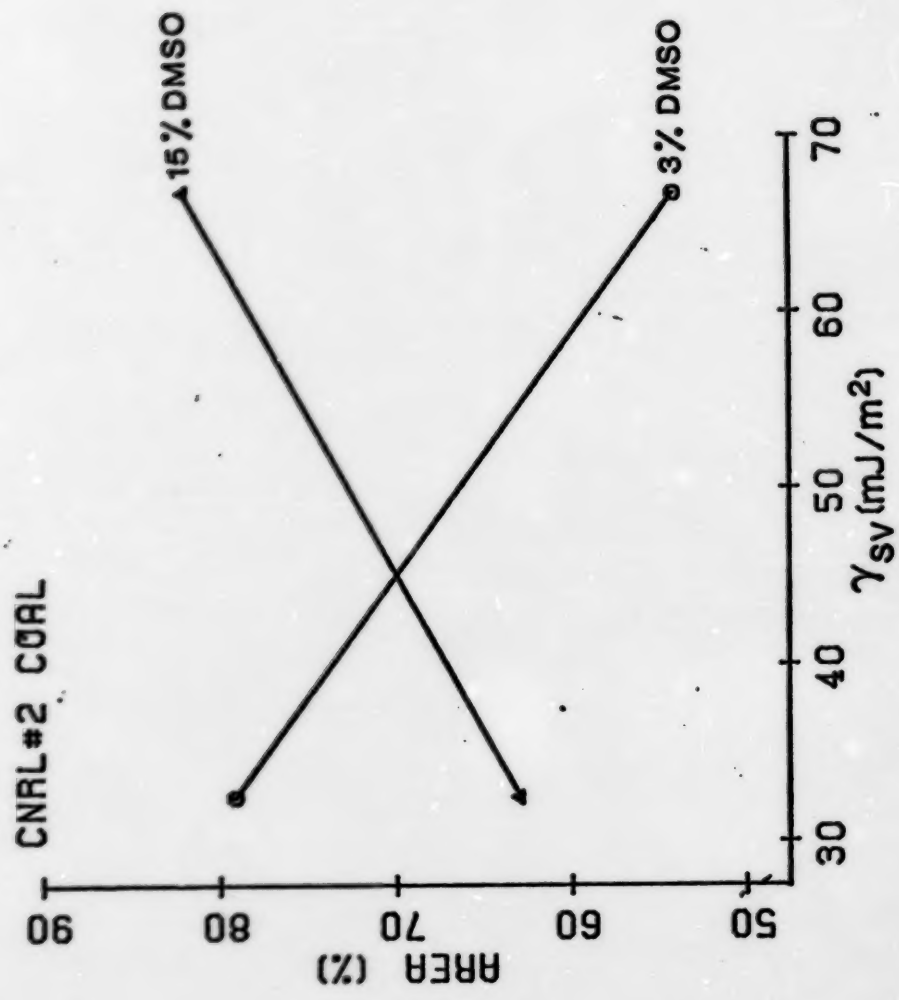

Figure 53. Substrate Area Covered by Adhering Particles as a Function of Surface Tension, γ_{SV}, of Substrate for CNRL #2 Coal

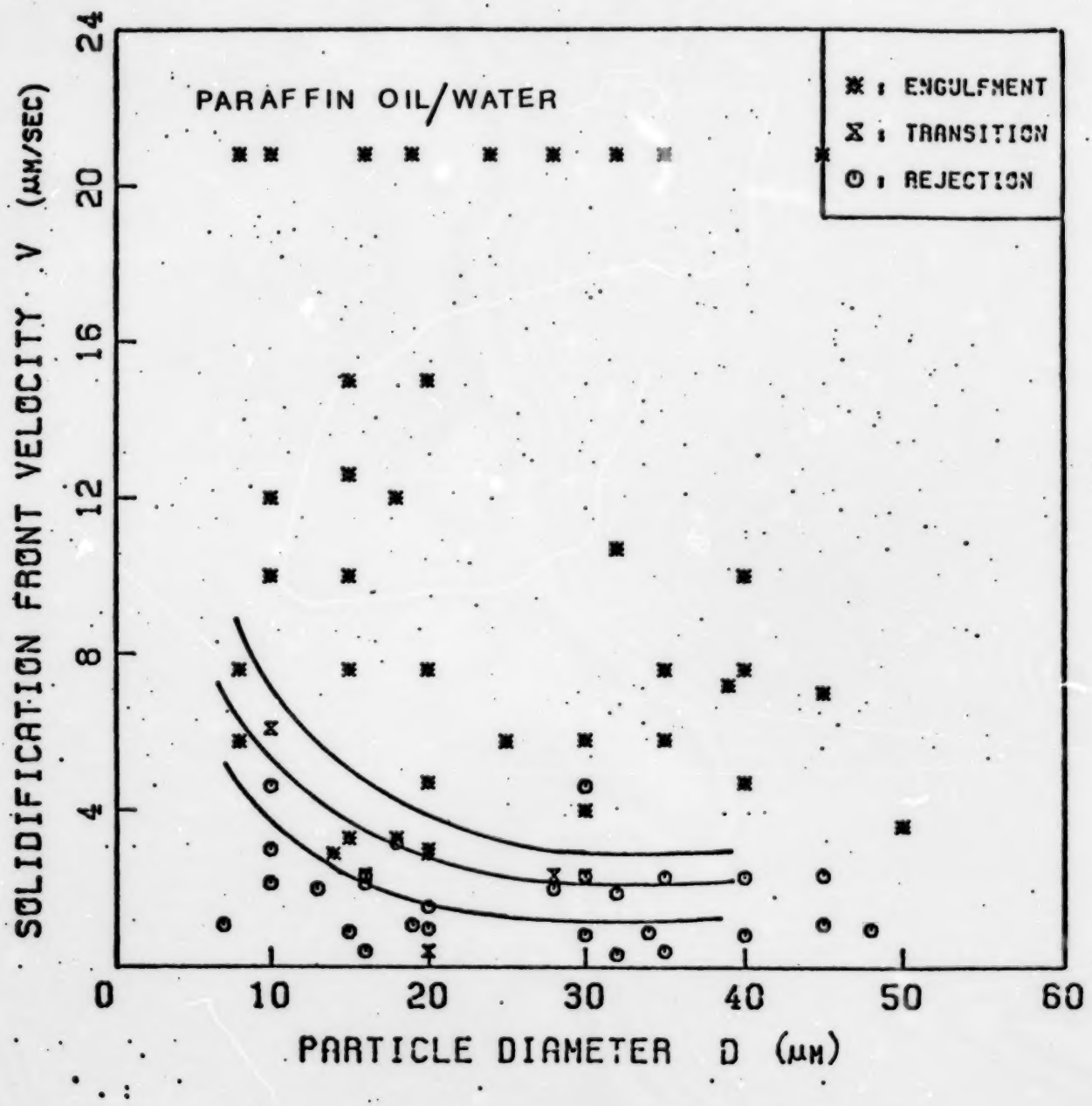

Figure 54. Solidification Front Velocity, V, versus Droplet Diameter, D, for Paraffin Oil/Water System

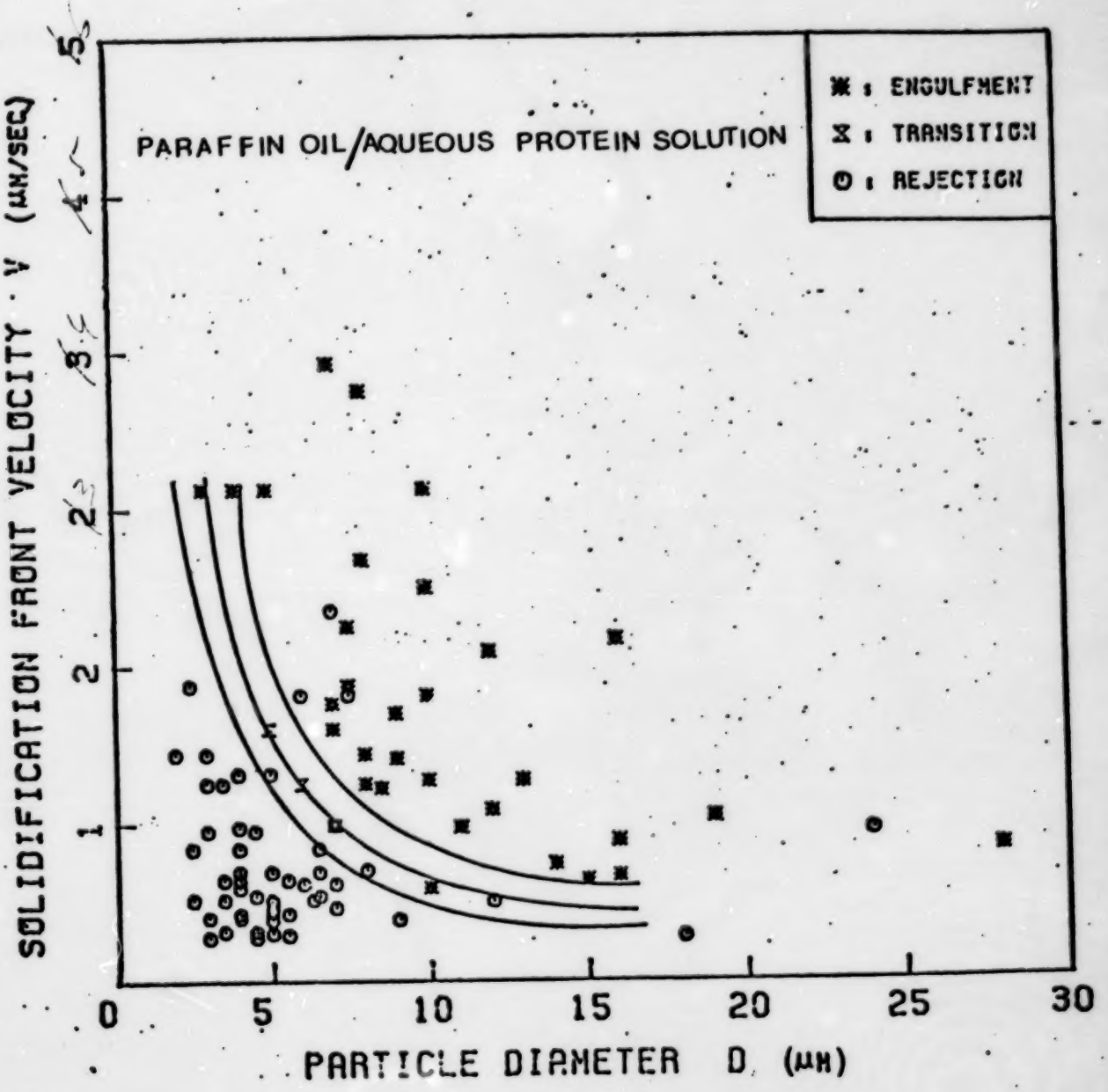

Figure 55. Solidification Front Velocity, V, versus Droplet Diameter, D, for Paraffin Oil/Protein Solution

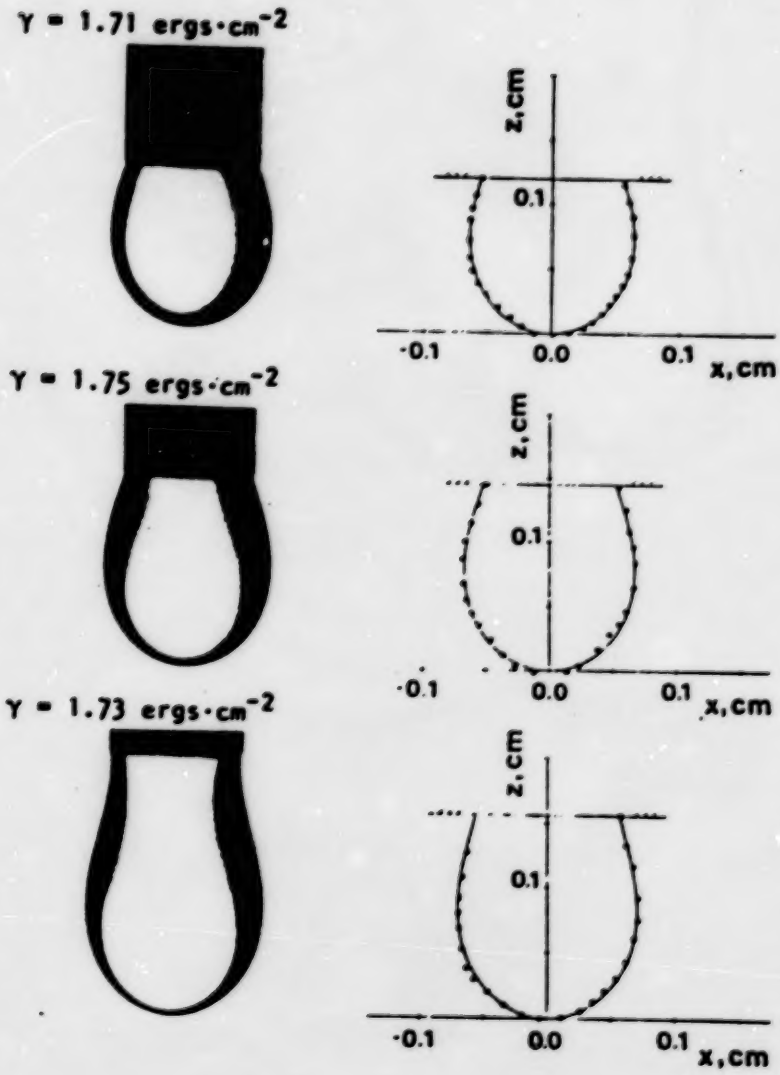

Figure 56. Pendant Drops of Water in Butanol and Their Profiles as Fitted by the Computer. γ is the Computed Interfacial Tension

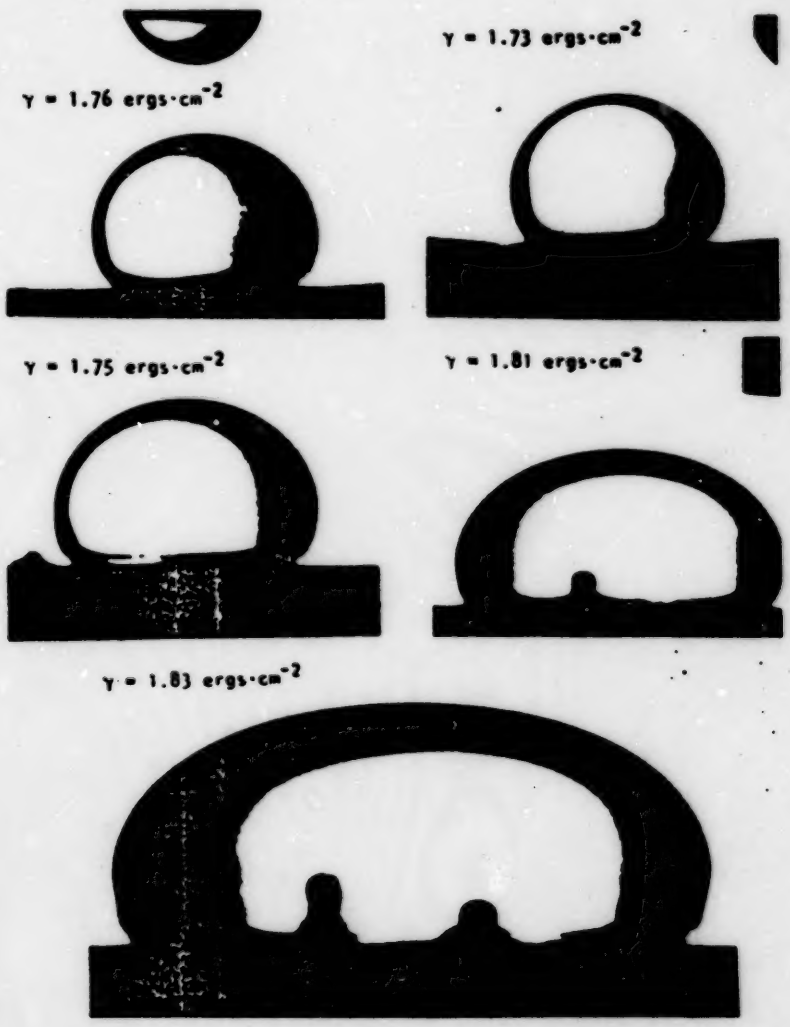

Figure 57. Sessile Drops of Water in Butanol. γ is the Computed Interfacial Tension. The Tip of a Pipette Shown in the Top, Left Figure is 1.05 mm in Diameter

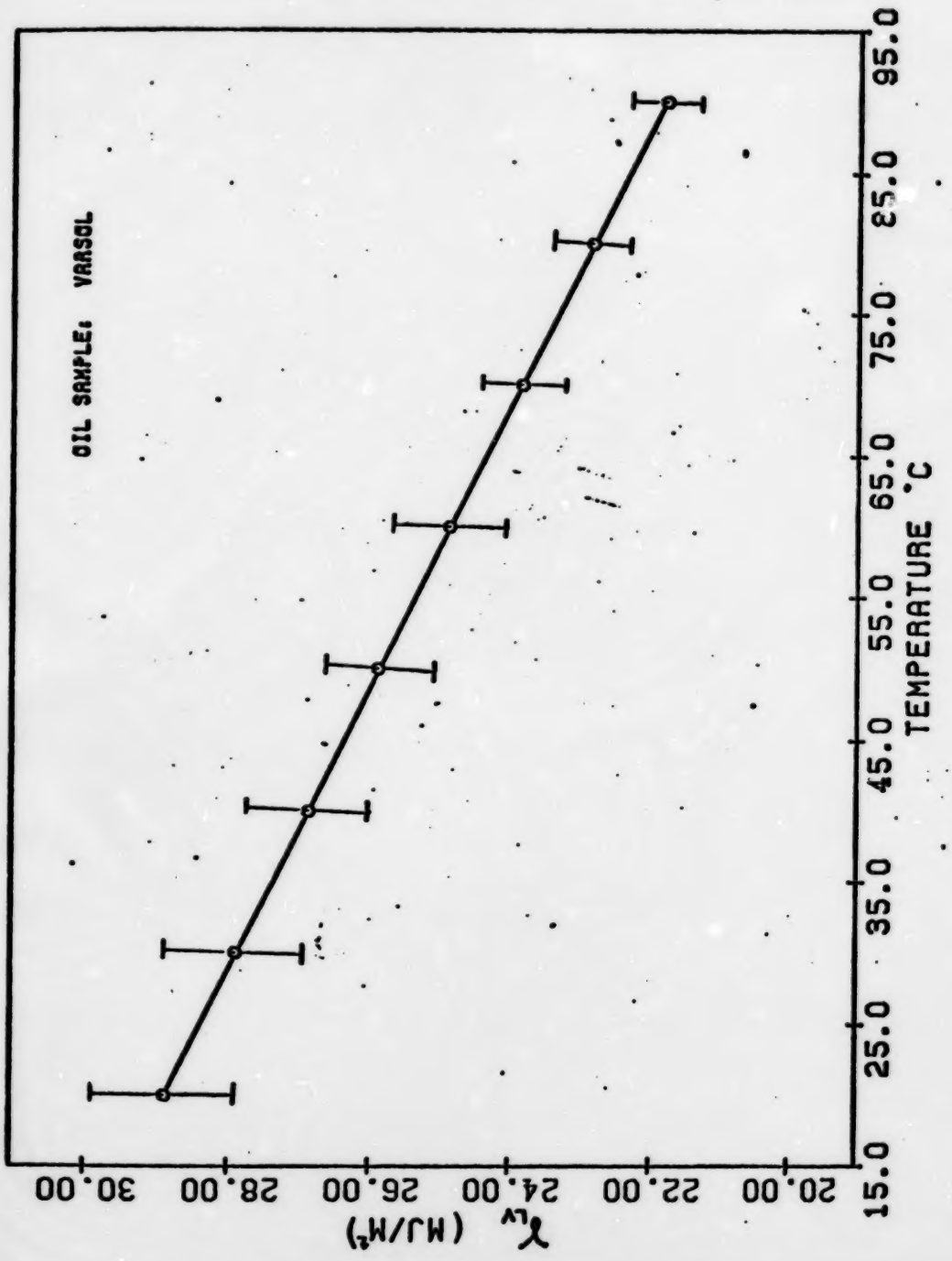

Figure 58. Surface Tension, γ_{LV}, of VARSOL as a Function of Temperature

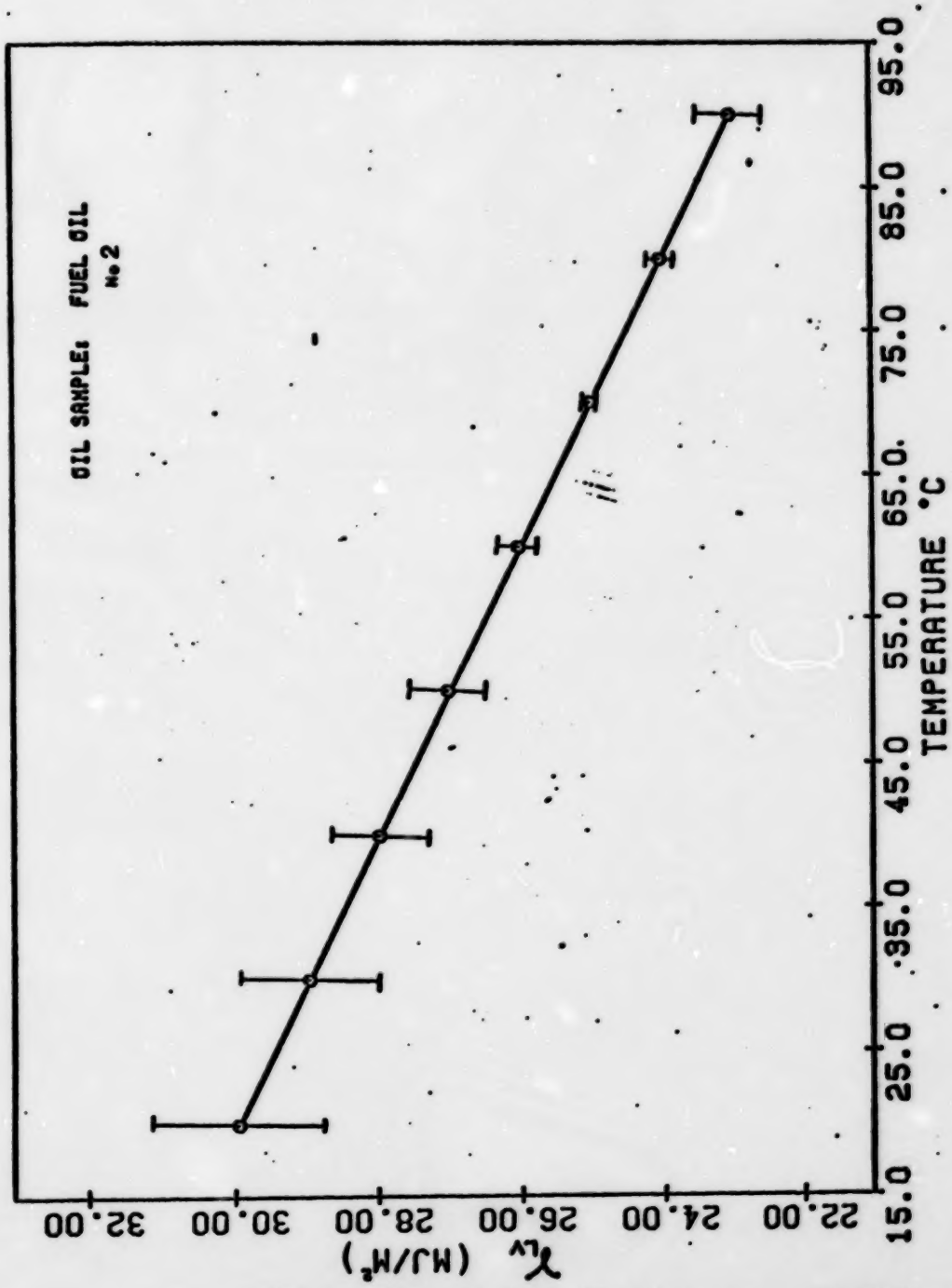

Figure 59. Surface Tension, γ_{LV}, of FUEL OIL No.2 as a Function of Temperature

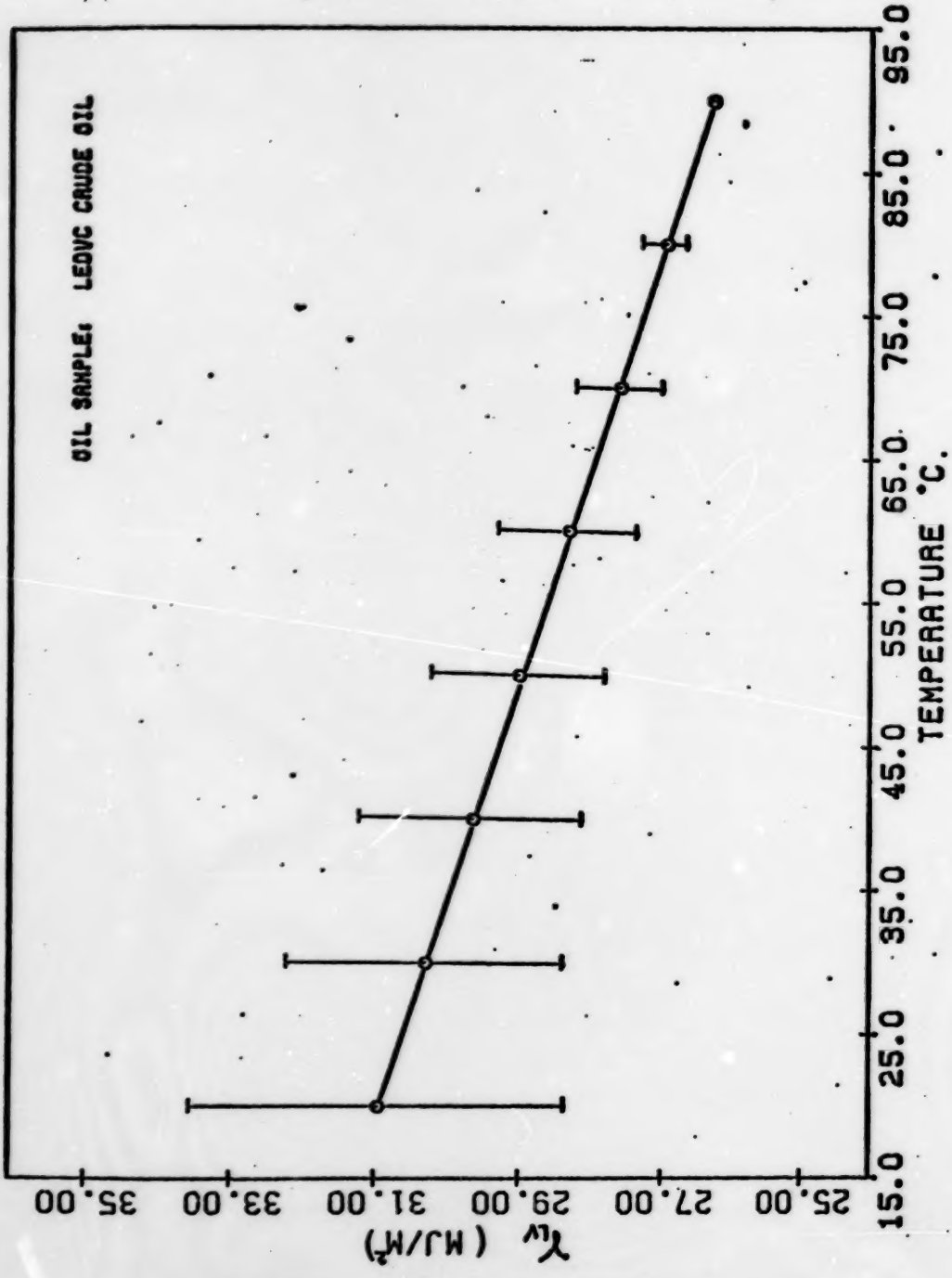

Figure 60. Surface Tension, γ_{LV}, of LEDUC CRUDE OIL as a Function of Temperature

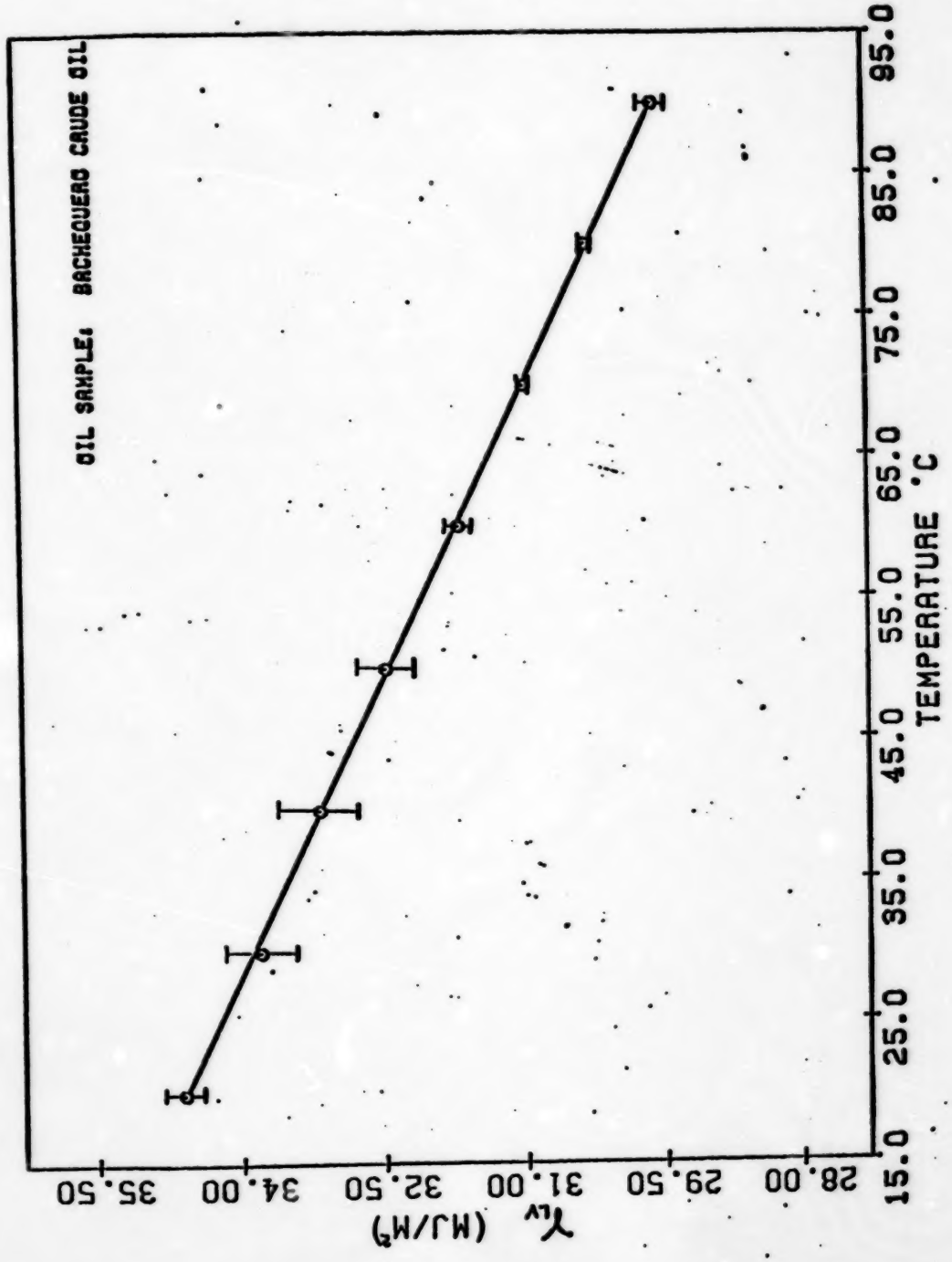

Figure 61. Surface Tension, γ_{LV}, of BACHEQUERO CRUDE OIL as a Function of Temperature

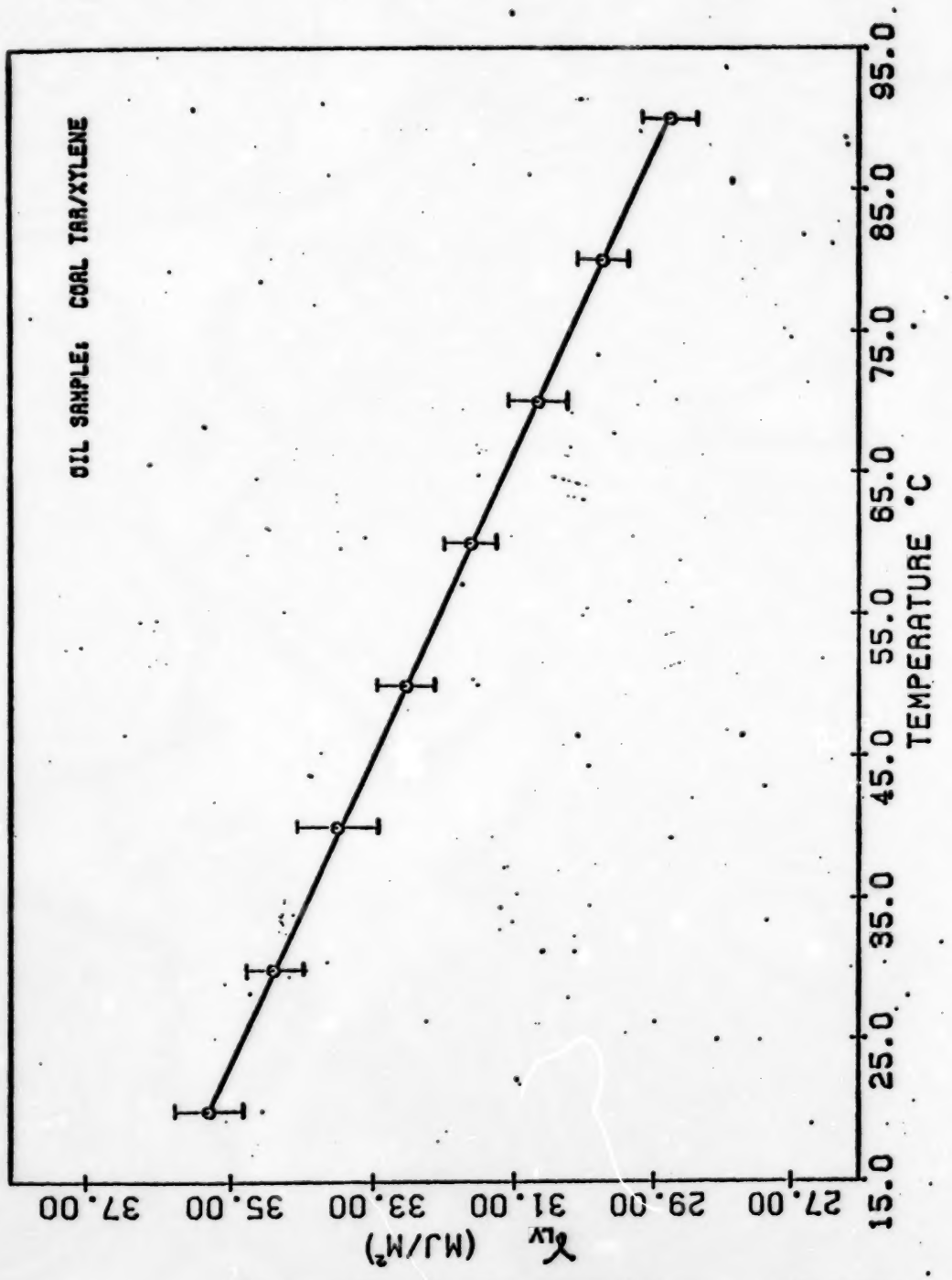

Figure 62. Surface Tension, γ_{LV}, of COAL TAR/XYLENE as a Function of Temperature

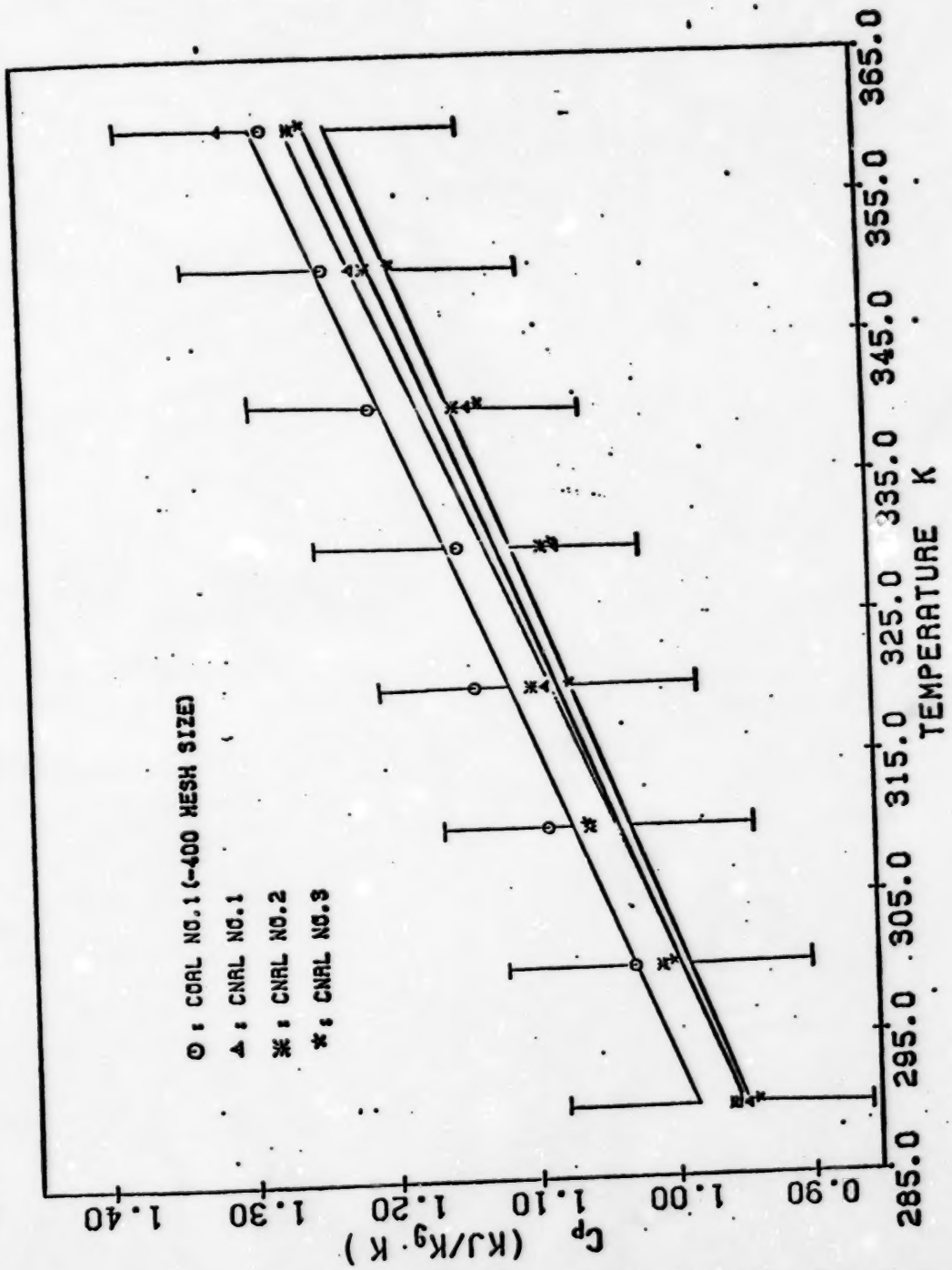

Figure 63. Specific Heat, C_p, as a Function of Temperature for Coal No.1 and CNRL #1, #2, #3 Coals

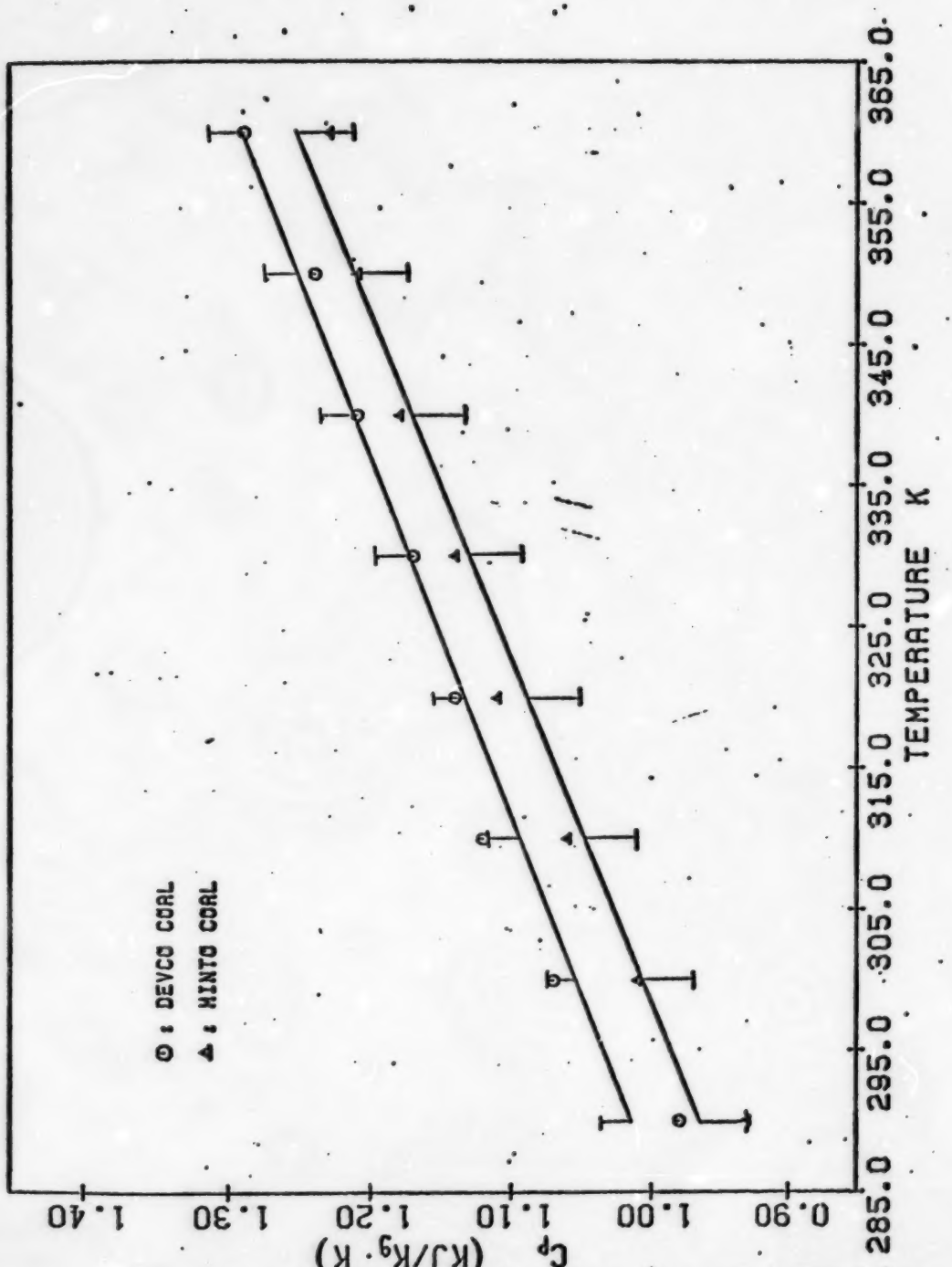

Figure 64. Specific Heat, C_p, as a Function of Temperature for DEVCO and MINTO Coals